Philadelphia University –Jordan
Electrical Engineering Department

Economics of Energy Resources

Lecture Notes

Dr.Prof.Mohammed Tawfeeq Lazim Al-Zuhairi

drmohamadtofik@yahoo.com

2008-2009

Economics of energy resources 1

1.1 Introduction

Economics of energy resources studies energy resources and energy conversion as well as energy utilization. It includes: studies various types and sources of energy existing in the nature highlighting their features, advantages and disadvantages. The studies will emphasis on converting the available energy resources into electrical form of energy. Demand of energy is derived from preferences for energy services and depends on properties of conversion technologies and costs. Energy commodities are economic substitutes. The study also recognizes: 1) energy is neither created nor destroyed but can be converted among forms (the First Law of Thermodynamics); 2) energy comes from the physical environment and ultimately returns there (the law of conservation of energy).

Economics of Energy

Energy economics is the field that studies human utilization of energy resources and energy commodities and the consequences of that utilization. In physical science terminology, "energy" is the capacity for doing work, e.g., lifting, accelerating, or heating material. In economic terminology, "energy" includes all energy commodities and energy resources, commodities or resources that embody significant amounts of physical energy and thus offer the ability to perform work. Energy commodities - e.g., gasoline, diesel fuel, natural gas, propane, coal, or electricity – can be used to provide energy services for human activities, such as lighting, space heating, water heating, cooking, motives power, electronic activity and electric power generation.

The state of energy at which it is available at the nature is also called the form of energy. The most familiar forms of energy used now days are: thermal, chemical, mechanical, electrical and nuclear. A physical system converts the energy in the form available to the required form of energy. This process is known as energy conversion.

Energy economic studies deal with finding economical supply of the energy resources, to convert those resources into other useful energy forms, to transport them to the users, to use them, and to dispose of the residuals. It studies roles of alternative market and regulatory structures on these activities, economic distributional impacts, and environmental consequences. It studies economically efficient provision and use of energy commodities and resources and factors that lead away from economic efficiency.

Energy resources

It is well known that the various sources of energy are:

1. Fossil fuel (coal, oil and gas) (chemical form of energy)
2. The sun (solar – heat energy)

3. Nuclear fuel	(nuclear form of energy)
4. Ocean tides	(potential energy)
5. Flowing rivers	(kinetic energy)
6. Geothermal energy	(heat energy)
7. Wind energy	(wind)

.

The well-known energy resources - e.g., crude oil, natural gas, coal, biomass, hydro, uranium, wind, sunlight, or geothermal deposits – can be harvested to produce energy commodities.

Properties of Energy Resources and Energy Commodities

Other than all embodying significant amounts of physical energy, energy resources or commodities vary greatly. They may embody chemical energy (e.g., oil, natural gas, coal, biomass), mechanical energy (e.g., wind, falling water), thermal energy (geothermal deposits), radiation (sunlight, infrared radiation), electrical energy (electricity), or the potential to create energy through nuclear reactions (uranium, plutonium.) They have differing physical forms.

Crude oil, most refined petroleum products, and water are liquids. Of water includes available energy only through its motion. Coal, most biomass, and uranium are solids. Natural gas and wind are in gases, with wind including available energy based only on its movement.

Geothermal energy is available through hot liquids (normally water) or solids (subterranean rock formations). Solar radiation is a pure form of energy. Electricity consists of electrons moving under an electrical potential.

Resources can be viewed as renewable or depletable. Some renewable resources can be stored; others are not storable. These issues will be discussed more fully in a subsequent sections.

Classifications of Energy Resources

Based on the speed of natural processes, one can classify primary energy resources as:

1. Nonrenewable (depletable) resources.
2. Renewable resources.

Renewable resources can be further subdivided into storable or nonstorable resources. Renewable resources are self-renewing within a time scale important for economic decision-making. Storable renewable resources typically exist as a stock, which can be used or can be stored. Biomass, hydro power, and some geothermal, falls in this category.

The amount used at one time influences the amount available in subsequent times. Nonstorable renewable resources – wind, solar radiation, run-of-the-river hydro resources can be used or not, but the quantity used at a given time has no direct influence on the quantity available subsequently. Most energy commodities are storable (refined petroleum products, processed natural gas, coal, batteries), but electricity is not storable as electricity. Depletable resources are those whose renewal speeds are so slow that it is appropriate to view them as made available once and only once by nature. Crude oil, natural gas, coal, and uranium all fall in this category.

Physical Properties of Common Energy Resources and Commodities

Resource/commodity	Energy Form	Physical Form	Time Scale
Coal	Chemical	Solid	Depletable resource,storable commodity
Crude Oil	Chemical	Liquid	Depletable resource
Natural Gas	Chemical	Gas	Depletable resource
Refined petroleum products	Chemical	Liquid	Storable commodity
Trees/Biomass	Chemical	Solid	Renewable ,storable resource
Wind	Mechanical	Moving gas	Renewable ,nonstorable resource
Hydro	Mechanical	Moving liquid	Renewable ,storable resource
Geothermal	Thermal	Solid or Liquid	Renewable or depletable resources
Uranium	Nuclear	Solid	Depletable resource
Solar radiation	Radiation	Pure energy	Renewable ,nonstorable resource
Battery	Chemical	Solid	Storable commodity
Electricity	Electrical	Moving electrons	Nonstorable commodity

Units of Energy

The fundamental of energy (mechanical)unit is a joule, which represents the work of a force of a Newton in moving a body through a distance of 1 m along the direction of force (1 J = 1 N x 1 m).
Electric power is the electric energy rate; its fundamental unit is a watt (1 W = 1 J/sec). . More commonly, electric energy is measured in kilowatt-hours (kWh):

$$1 \text{ kWh} = 3.6 \times 10^6 \, J \qquad (1.1)$$

Thermal energy is usually measured in calories. By definition, one metric calorie (1 cal) is the amount of heat required to raise the temperature of 1 g of water from 15 to 16°C. The kilocalorie is even more common (1 kcal= 10^3 cal).A standard calorific value for coal is 27.91MJ/kg (kJ / gram).

As energy is a unified concept, as expected, the joule and calorie are directly proportional:

$$1 \text{ cal} = 4.186 \, J \qquad (1.2)$$

A larger unit for thermal energy is the British thermal unit, Btu (the energy required to increase the temperature of 1 pound of water by 1°F).

$$1 \text{ BTU} = 1{,}055\ J = 252 \text{ cal} \qquad (1.3)$$

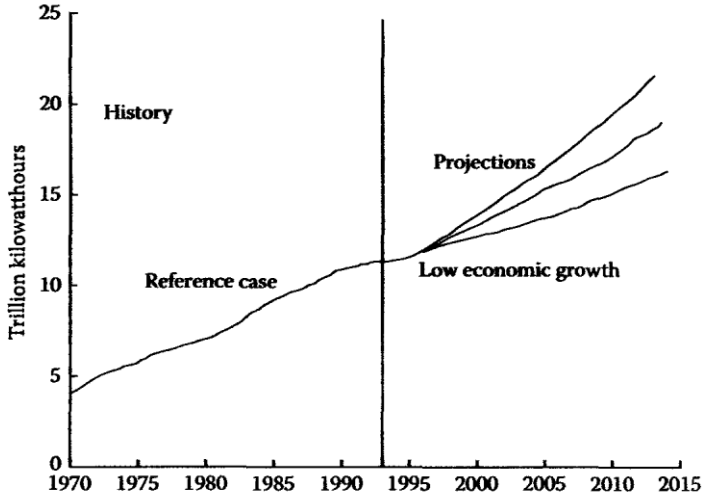


FIGURE 1.1 Typical annual world energy requirements.

A still larger unit is the quad (quadrillion Btu):

$$1 \text{ quad} = 10^{15} \text{ BTU} = 1.055 \times 10^{18} \text{ J} \qquad (1.4)$$

In the year 2000, the world used about 14×10^{12} kWh of energy an amount above most projections (Figure 1.1). An annual growth of 3.3 to 4.3% was typical for world energy consumption in the 1990 to 2000 period. A slightly lower rate is forecasted for the next 30 years.

1.2 Major Energy Resources

The energy resources can be divided into two categories: nonrenewable and renewable.

1.2.1 Nonrenewable Resources

Nonrenewable resources cannot be replenished. We have limited supplies of them, and when these supplies are gone we will not have any more. Nonrenewable resources are**: Fossil fuels and Nuclear energy.**

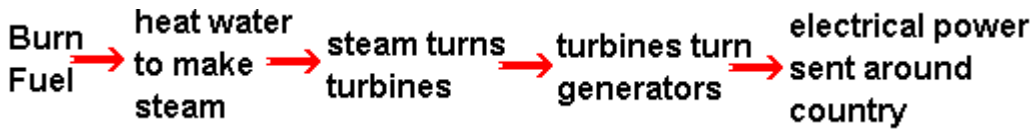
Fossil fuels were formed from the fossilized remains of tiny plants and animals that lived long ago. Most electricity used in the world is generated from power plants that burn fossil fuels to heat water and make steam. The highly pressurized steam is directed at blades to make them spin.

The three forms of fossil fuels are coal, oil, and natural gas.

1. Coal is a hard, black, rock-like substance made up of carbon, hydrogen, oxygen, nitrogen, and sulphur. There are three main types of coal: anthracite, bituminous, and lignite. Coal is found in many parts of the world.

2. Oil is a liquid fossil fuel, sometimes also called petroleum. It is found underground within porous rocks.

3. Natural gas is made up primarily of a gas called methane. Methane gas is highly flammable and burns very cleanly. Natural gas is usually found underground along with oil. It is pumped up and travels through pipelines to homes and businesses **Coal**, **oil** and **gas** provided around 66% of the world's electrical power, and 95% of the world's total energy demands (including heating, transport, electricity generation and other uses).



Other fossil fuels are being investigated, such as bituminous sands and oil shale. The difficulty is that they need expensive processing before we can use them.

Fossil fuel World reserves

Before embarking on this more abstract analysis we can stay briefly with the conventional idea of energy resources by looking at the way 'proved reserves' of oil, gas and coal were distributed around the world in 2001 (Figures1.2, 1.3 and 1.4). Since the industrial revolution, national prosperity has been intimately linked with ready access to these fossil fuels. So current perceptions about the amounts of these three fuels now available give an instant image of powerful economic and political influences at work at the beginning of the twenty-one century.

Figures 1.2, 1.3 and 1.4 (which use data from the oil industry) show the map of the world with proportional representations of proved reserves of the three fuels. The quoted proved reserves of oil and gas have actually increased over the past 30 years as a result of exploration and changing economic conditions, in spite of the large consumption. This process may well continue for some time as demand increases, though it evidently cannot do so indefinitely. What these maps do not show is the relation of these reserves to world demand. This is conveyed by a figure for how long the reserves would last at current extraction rates. This turned out to be for oil (in 2001) 50 years averaged over the whole world, but ranging from a mere 10 years for the UK and 19 for North America to nearly 100 years for several Middle Eastern states. For natural gas, the picture presented in Figure 1.4 is not much more comfortable: Eastern Europe and Russia now outstrip the Middle East. For the world, the 'life' at current extraction rates is about 66 years, but again the UK and USA have under 10 years, while Eastern Europe/Russia have 80 years and several Middle Eastern states have over 100 years. Only for the original industrial fuel, coal (Figure 1.2), is the distribution more even throughout the world, with projected lives at current consumption rates of over 200 years.

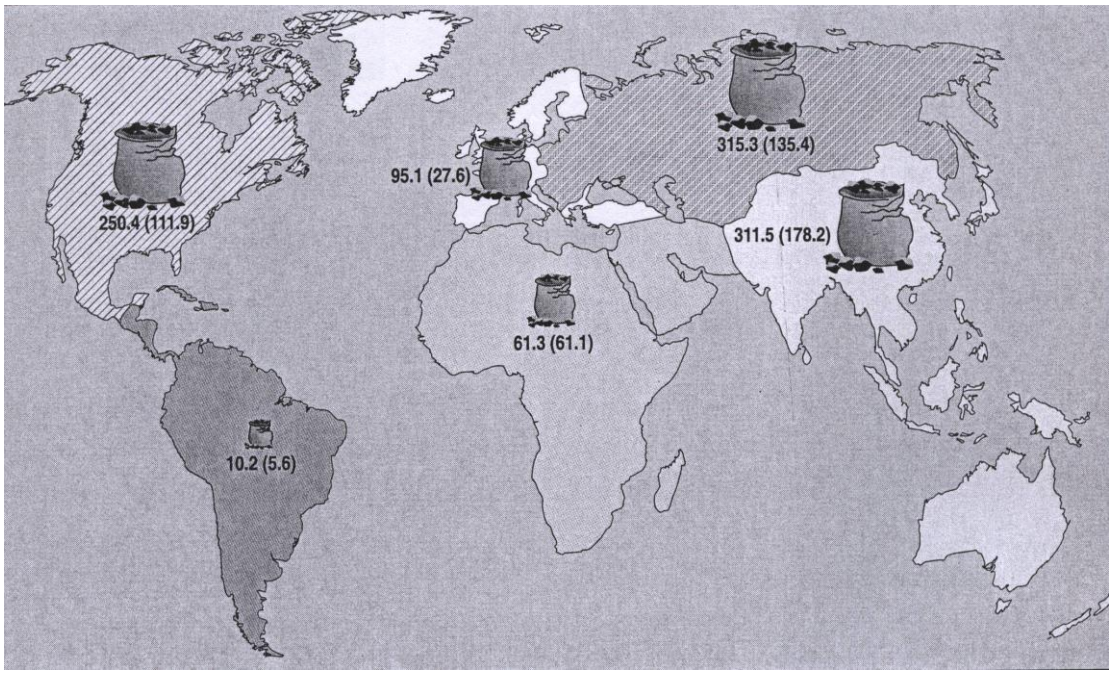


Fig.1.2 Coal proved reserves (thousand million tones), global distribution, 2001.

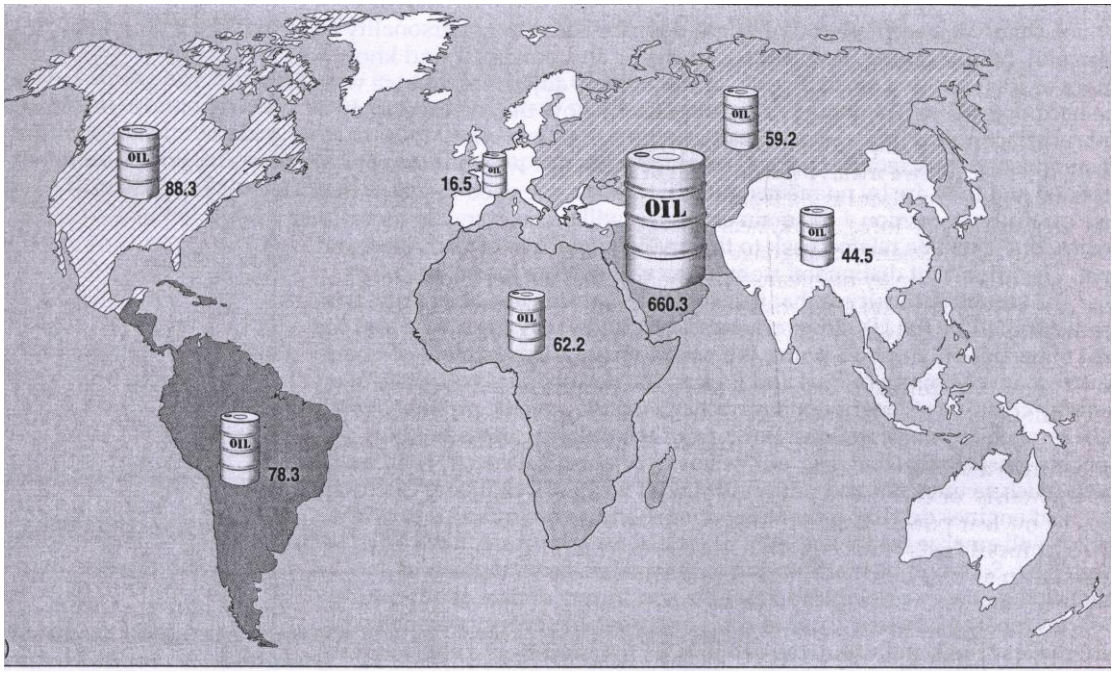


Fig.1.3 Oil: proved reserves (billion barrels), global distribution, 2001.

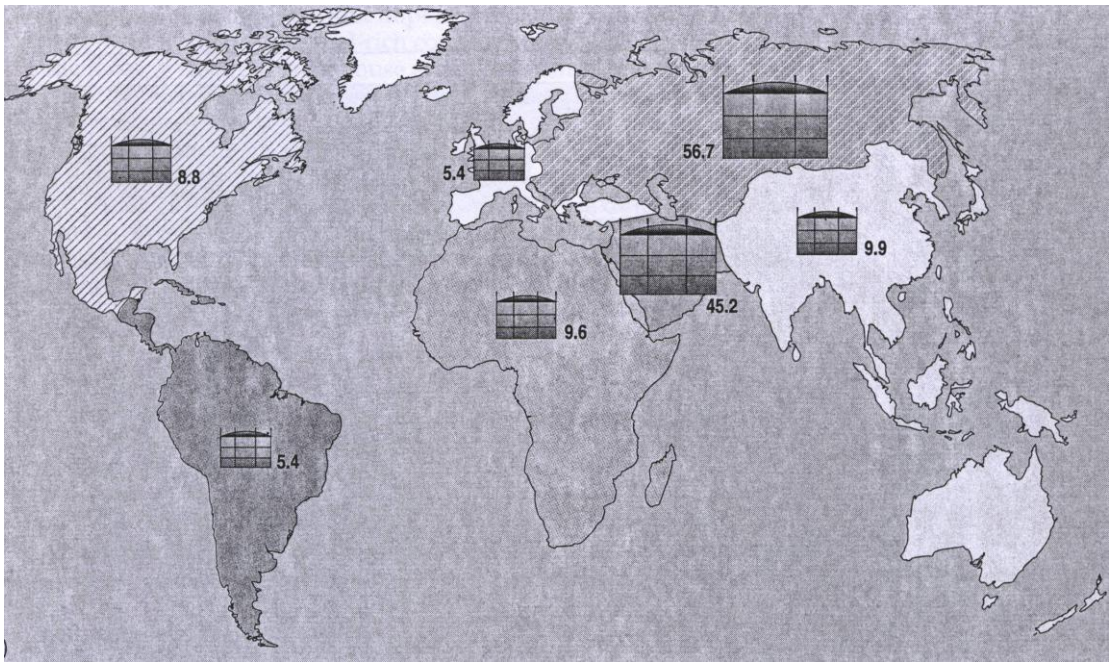


Fig.1.4 Natural gas: proved reserves (trillion m^3), global distribution, 2001.

With the current annual growth in energy consumption, the fossil fuel supplies of the world will be depleted in, at best, a few hundred years, unless we switch to other sources of energy or use energy conservation to tame energy consumption without compromising quality of life.

The estimated world reserves of fossil fuel [1] and their energy density are shown inTable1.1. With a doubling time of energy consumption of 14 years, if only coal would be used, the whole coal reserve would be depleted in about 125 years. Even if the reserves of fossil fuels were large, their predominant or exclusive usage is not feasible due to environmental, economical, and even political reasons. Alternative energy sources are to be used increasingly; with fossil fuels used slightly less, gradually, and more efficiently than today.

TABLE 1.1 Estimated Fossil Fuel Reserves

Fuel	Estimated Reserves	Energy Density in Watthours (Wh)
Coal	7.6×10^{12} metric tons	937 per ton
Petroleum	2×10^{12} barrels	168 per barrel
Natural gas	10^{16} ft^3	0.036 per ft^3

Advantages and Disadvantages of Fossil Fuels

Advantages

- Very large amounts of electricity can be generated in one place using coal, fairly cheaply.
- Transporting oil and gas to the power stations is easy.
- Gas-fired power stations are very efficient.

A fossil-fuelled power station can be built almost anywhere, so long as you can get large quantities of fuel to it.

Disadvantages

- Basically, the main drawback of fossil fuels is pollution.
  Burning any fossil fuel produces carbon dioxide, which contributes to the "greenhouse effect", warming the Earth.

Burning coal produces more carbon dioxide than burning oil or gas. It also produces sulphur dioxide, a gas that contributes to acid rain. We can reduce this before releasing the waste gases into the atmosphere.

- Mining coal can be difficult and dangerous. Strip mining destroys large areas of the landscape.
- Coal-fired power stations need huge amounts of fuel, which means train-loads of coal almost constantly. In order to cope with changing demands for power, the station needs reserves.
  This means covering a large area of countryside next to the power station with piles of coal.

1.2.2 NUCLEAR (URANIUM) ENERGY

NUCLEAR ENERGY IS ENERGY FROM ATOMS

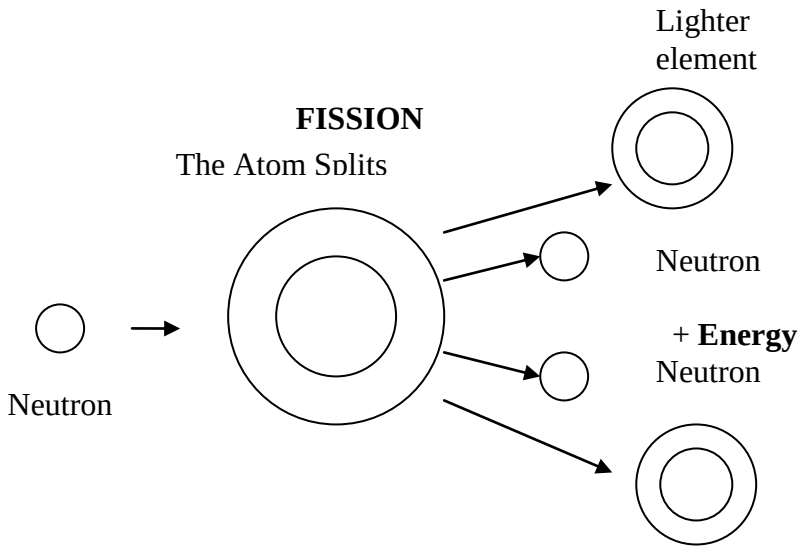
Nuclear energy is energy in the nucleus (core) of an atom. There is enormous energy in the bonds that hold atoms together. Nuclear energy can be used to make electricity. But first the energy must be released. It can be released from atoms in two ways: nuclear **fusion** and nuclear **fission**.

In **nuclear fusion**, energy is released when atoms are combined or fused together to form a larger atom. This is how the sun produces energy.

In **nuclear fission**, atoms are split apart to form smaller atoms, releasing energy. Nuclear power plants use nuclear fission to produce electricity.

NUCLEAR FUEL - URANIUM

The fuel most widely used by nuclear plants for nuclear fission is uranium. Uranium is nonrenewable, though it is a common metal found in rocks all over the world. Nuclear plants use a certain kind of uranium, U-235, as fuel because its atoms are easily split apart.



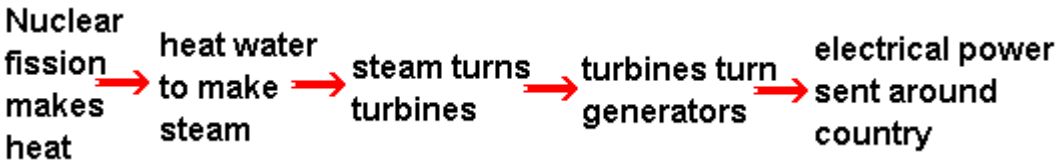
During nuclear fission, a neutron hits the uranium atom and split it into two lighter atoms, releasing a great amount of energy as heat and radiation .in this fission process two more neutrons are also released. These neutrons go on to bombard other uranium

atoms, and the process repeats itself over and over again. This is called a chain reaction. The reaction is therefore produces a significant amount of energy.

Nuclear Power - energy from splitting Uranium atoms

Nuclear power produces around 11% of the world's energy needs, and produces huge amounts of energy from small amounts of fuel, without the pollution that you'd get from burning fossil fuels.

How it works


Nuclear fission makes heat
heat water to make steam
steam turns turbines
turbines turn generators
electrical power sent around country

- Nuclear power stations work in pretty much the same way as fossil fuel-burning stations, except that a "chain reaction" inside a nuclear reactor makes the heat instead.
- The reactor uses Uranium rods as fuel, and the heat is generated by **nuclear fission**. Neutrons smash into the nucleus of the uranium atoms, which split roughly in half and release energy in the form of heat.
- Carbon dioxide gas is pumped through the reactor to take the heat away, and the hot gas then heats water to make steam which drive generators turbines .

The reactor is controlled with "control rods", made of boron, which absorb neutrons. When the rods are lowered into the reactor, they absorb more neutrons and the fission process slows down. To generate more power, the rods are raised and more neutrons can crash into uranium atoms.

Natural uranium is only 0.7% "uranium-235", which is the type of uranium that undergoes fission in this type of reactor.
The rest is U-238, which just sits there getting in the way.

Advantages

- Nuclear power costs about the same as coal, so it's not expensive to make.
- Does not produce smoke or carbon dioxide, so it does not contribute to the greenhouse effect.
- Produces huge amounts of energy from small

amounts of fuel.

- Produces small amounts of waste.
- Nuclear power is reliable.

Disadvantages

- Although not much waste is produced, it is very, very dangerous.
  It must be sealed up and buried for many years to allow the radioactivity to die away.
- Nuclear power is reliable, but a lot of money has to be spent on safety - if it **does** go wrong, a nuclear accident can be a major disaster.
  People are increasingly concerned about this - in the 1990's nuclear power was the fastest-growing source of power in much of the world. In 2005 it was the second slowest-growing.

Is it renewable?

Nuclear energy from Uranium is **not** renewable.
Once we've dug up all the Earth's uranium and used it, there isn't any more.

1.3 Renewable Energy

There is considerable international effort into the development of alternative energy sources to supplement fossil oil. Large interest is focused on renewable energy, particularly solar and wind energy, biomass and hot rock geothermal.

1. ***SOLAR ENERGY***

The sun is the primary source of energy .The radiated heat by the sun can be utilized in water heating and generation of electricity. Solar energy is readily harnessed for low temperature heat and in many places domestic hot water units with storage routinely utilize it. The average incident solar energy received on the earths surface is about 1000W/ m^2 , but the actual value varies considerably In Europe much less than this is received through much of the year, for instance in winter most of Europe averages less than 1 kWh/m^2 per day (on a horizontal surface).

However, for electricity generation, solar power has limited potential, due to being diffuse and intermittent. First, solar input is interrupted by night and by cloud cover, which means that solar electric generation inevitably has a low capacity factor, typically less than 15%. Also, there is a low intensity of incoming radiation and converting this to high-grade electricity is still relatively inefficient (12 - 16 percent), though it has been the subject of much research over several decades.

Two methods of converting the sun's radiant energy to electricity are the focus of attention. The better known method utilizes sunlight acting on **photovoltaic cells** to produce electricity. These can readily be mounted on buildings without any aesthetic intrusion or requiring special support structures. Solar photovoltaic (PV) has application on satellites and for certain earthbound signaling and communication equipment. The cost per unit of electricity is at least ten times that of conventional sources, so it limits its potential to supplementary applications on buildings where its maximum supply coincides with peak demand.

For a stand-alone system some means must be employed to store the collected energy during hours of darkness or cloud - either as electricity in batteries, or in some other form such as hydrogen (produced by electrolysis of water). In either case, an extra stage of energy conversion is involved with consequent energy losses, thus lowering overall net efficiency, and greatly increasing capital costs.

A **solar thermal** power plant has a system of mirrors to concentrate the sunlight on to an absorber, the energy then being used to drive turbines. The concentrator is usually a parabolic mirror trough oriented north-south, which tracks the sun's path through the

day. The absorber is located at the focal point and converts the solar radiation to heat (about 400^{o}C) which is transferred into a fluid such as synthetic oil. The fluid drives a conventional turbine and generator. Several such installations in modules of 80 MW are now operating. Each module requires about 50 hectares of land and needs very precise engineering and control. These plants are supplemented by a gas-fired boiler which generates about a quarter of the overall power output and keeps them warm overnight. Power costs are two to three times that of conventional sources.

2. ***WIND ENERGY***

The wind produced by the sun has got sufficient energy, which can be utilized in windmills to drive generators. Such generators are used for charging batteries for continuous operation.

Wind turbines of up to 5 MW are now functioning in many countries. The power output is a function of the cube of the wind speed, so doubling the wind speed gives eight times the energy potential. Hence such turbines require a wind in the range 4 to 25 meters/second (14 - 90 km/hr), with maximum output being at 12-25 m/s (the excess energy being spilled above 25 m/s). In practice relatively few areas have significant prevailing winds, but many have enough to be harnessed. Like solar, consumers depending on wind power requires alternative power sources to cope with calmer periods.

Wind turbines have a high steel tower to mount the generator nacelle, and have rotors with three blades up to 50m long. Foundations require hundreds of cubic meters of reinforced concrete.

Generation costs are greater than those for coal or nuclear, and allowing for backup capacity and grid connection complexities make it about double.

3. ***RIVERS***

Hydroelectric power, using the potential energy of rivers, now supplies 17.5% of world electricity (99% in Norway, 57% in Canada, 55% in Switzerland, 40% in Sweden, 7% in USA). Apart from a few countries with an abundance of it, hydro capacity is normally applied to peak-load demand, because it is so readily stopped and started.

The chief advantage of hydro systems is their capacity to handle seasonal (as well as daily) high peak loads. In practice the utilization of stored water is sometimes complicated by demands for irrigation, which may occur out of phase with peak electrical demands.

4. ***GEOTHERMAL***

Where hot underground steam can be tapped and brought to the surface it may be used to generate electricity. Such geothermal sources have potential in certain parts of the world such as New Zealand, USA, Philippines and Italy. Some 8000 MW of capacity is operating, including 3000 MW in the USA and 2000 MW in Philippines, and in 2002 geothermal produced more electricity than did wind worldwide. Geothermal electric output is expected to triple by 2030.

5. ***TIDES***

There is a tremendous energy in the ocean tides and waves but it is very difficult to harness this power for generating electricity. Harnessing the tides in a bay or estuary has been achieved in France (since 1966), Canada and Russia, and could be achieved in certain other areas where there is a large tidal range. The trapped water can be used to turn turbines as it is released through the tidal barrage in either direction. Worldwide this technology appears to have little potential, largely due to environmental constraints.

5.***WAVES***

Harnessing power from wave motion is a possibility, which might yield much more energy than tides. The feasibility of this has been investigated, particularly in the UK. Generators either coupled to floating devices or turned by air displaced by waves in a hollow concrete structure would produce electricity for delivery to shore. Numerous practical problems have frustrated progress, not least storm damage.

6. ***OCEAN THERMAL***

Ocean thermal energy conversion (OTEC) has long been an attractive idea, but is unproven. It would work by utilizing the temperature difference between equatorial surface waters and cool deep waters via a submerged chimney arrangement, the temperature difference needing to be about 20 degrees top to bottom.

7. ***BIOFUELS***

Growing crops of wood or other kinds to burn directly or to make fuels such as ethanol and biodiesel has a lot of support in several parts of the world, though mostly focused on transport fuel. The man issues here are land and water resources. The land usually must either be removed from agriculture for food or fiber, or it means encroaching upon forests or natural ecosystems. But available fresh water for growing biofuel crops such as maize and sugarcane may be an even greater constraint.

Burning biomass for generating electricity has some appeal as a means of utilizing solar energy for power. However, the logistics usually defeat it, in that a lot of energy is required to harvest and move the crops to the power station and for long term sustainability the ash containing mineral nutrients needs to be returned to the land. In Australia and Latin America sugar cane pulp is burned as a valuable energy source, but this (biogases) is a by-product of the sugar.

1.4 Comparisons of various energy sources

Every form of energy generation has advantages and disadvantages as shown in the table below.

Source	*Advantages*	*Disadvantages*
Coal	• Inexpensive • Easy to recover (in U.S. and Russia)	• Requires expensive air pollution controls (e.g. mercury, sulfur dioxide) • Significant contributor to acid rain and global warming • Requires extensive transportation system
Nuclear	• Fuel is inexpensive • Energy generation is the most concentrated source • Waste is more compact than any source • Extensive scientific basis for the cycle • Easy to transport as new fuel • No greenhouse or acid rain effects	• Requires larger capital cost because of emergency, containment, radioactive waste and storage systems • Requires resolution of the long-term high level waste storage issue in most countries • Potential nuclear proliferation issue
Gas / Oil	• Good distribution system for current use levels • Easy to obtain • Better as space heating energy source	• Very limited availability as shown by shortages during winters several years ago • Could be major contributor to global warming • Expensive for energy generation • Large price swings with supply and demand

		• Need 3x the amount of installed generation to meet demand
Wind	• Wind is free if available • Good source for periodic water pumping demands of farms as used earlier in 1900's • Generation and maintenance costs have decreased. Wind is proving to be a reasonable cost renewable source. • Well suited to rural areas.	• Limited to windy areas. • Limited to small generator size; need many towers. • Need expensive energy storage (e.g. batteries) • Highly climate dependent - wind can damage equipment during windstorms or not turn during still summer days. • Can affect endangered birds, however tower design can reduce impact..
Solar	• Sunlight is free when available	• Limited to southern areas of U.S. and other sunny areas throughout the world (demand can be highest when least available, e.g winter solar heating) • Does require special materials for mirrors/panels that can affect environment • Current technology requires large amounts of land for small amounts of energy generation

1.5 Electric Power Generation Limitations

Factors limiting electric energy conversion are related to the availability of various fuels, technical constraints, and ecological, social, and economical issues.Ecological limitations include those due to excess low-temperature heat and carbon dioxide (solid particles) and oxides of sulfur nitrogen emissions from fuel burning.

Low-temperature heat exhaust is typical in any thermal energy conversion. When too large, this heat increases the earth's surface temperature and, together with the emission of carbon dioxide and certain solid particles, has intricate effects on the climate Global warming and climate changes appear to be caused by burning too much fossil fuel .Since the Three Mile Island and Chernobyl incidents, safe nuclear electric energy production has become not only a technical issue, but also an ever-increasing social (public acceptance) problem. Even hydro- and wind-energy conversion pose some environmental problems, though much smaller than those from fossil or nuclear fuel—energy conversion. Consequently, in forecasting the growth of electric energy consumption on Earth, we must consider all of these complex limiting Shifting to more renewable energy sources (wind, hydro, tidal, solar, etc.), while using combined heat-electricity production from fossil fuels to increase the energy conversion factor, together with intelligent energy conservation, albeit complicated, may be the only way to increase material prosperity and remain in harmony with the environment.

1.6 Electric Power Generation

Electric energy (power) is produced by coupling a prime mover that converts the mechanical energy (called a turbine) to an electrical generator, which then converts the mechanical energy into electrical energy (Figure l.5a through Figure l.5e). An intermediate form of energy is used for storage in the electrical generator. This is the so-called magnetic energy stored mainly between the stator (primary) and rotor (secondary). The main types of "turbines" or prime movers are as follows:

• Steam turbines

• Gas turbines

• Hydraulic turbines

• Wind turbines

• Diesel engines

• Internal combustion (IC) engines

The self-explanatory (Fig.1.5) illustrates the most used technologies to produce electric energy. They all use a prime mover that outputs mechanical energy .There are also direct electric energy production methods that avoid the mechanical energy stage, such as photovoltaic, thermoelectric, and electrochemical (fuel cells) technologies. As they do not use electric generators, and still represent only a tiny part of all electric energy produced on Earth, discussion of these methods falls beyond the scope of this course.
The steam (or gas) turbines in various configurations make use of practically all fossil fuels, from coal to natural gas and oil and nuclear fuel to geothermal energy inside the earth.

Usually, their efficiency reaches 40%, but in a combined cycle (producing heat and mechanical power), their efficiency recently reached 55 to 60%. Powers per unit go as high 300 MW and more at 3000 rpm but, for lower powers, in the MW range, higher speeds are feasible to reduce weight (volume) per power.

Recently, low-power high-speed gas turbines (with combined cycles) in the range of 100 kW at 70,000 to 80,000 rpm became available. Electric generators to match this variety of powers and speeds were also recently produced.

Diesel engines (Figure 1.5b) drive the electric generators on board ships and trains.

In vehicles, electric energy is used for various tasks for powers up to a few tens of kilowatts, in general. The internal combustion (or diesel) engine drives an electric generator (alternator) directly or through a belt transmission (Figure I.5c).

Hydraulic potential energy is converted to mechanical potential energy in hydraulic energy turbines. They, in turn, drive electric generators to produce electric energy In general, the speed of hydraulic turbines is rather low — below 500 rpm, but in many cases, below 100 rpm.

The speed depends on the water head and flow rate. High water head leads to higher speed; while high flow rate leads to lower speeds Hydraulic turbines for low, medium, and high water heads were perfected in a few favored embodiments (Kaplan, Pelton, Francis, bulb type, Strafflo, etc).

With a few exceptions — in Africa, Asia, Iraq, Russia, China, and South America — many large power/unit water energy reservoirs were provided with hydroelectric power plants with large power potentials (in the hundreds and thousands of megawatts). Still, by 2007, only 20% of the world's 900,000MW reserves were put to work.

Fuel Cost

The following table gives a comparison between the various types of fuels used in electricity generation:

No.	Fuel type		Cost (2007) Fuel Price ($ / MBTU)
1	Coal	High Sulpher	2.0
		Low Sulpher	3.0
2	Natural Gas		6.0
3	Crud Oil	High Sulpher	12.0
		Low Sulpher	14.0
4	Distillate Oil (No.2)		14.0
5	Oil (Bunker C) (No.6)		12.0
6	Nuclear		0.9

The fuel costs presented here are useful only for comparison:

- In general the nuclear fuel cost is the lowest, and does not vary much with the plant location.
- In contrast to nuclear fuel, the delivery cost of coal varies directly with the distance between the coal and plant site.
- Of all fuel used for electric power plants, oil is the most expensive because the oil prices subjected to huge price fluctuation.

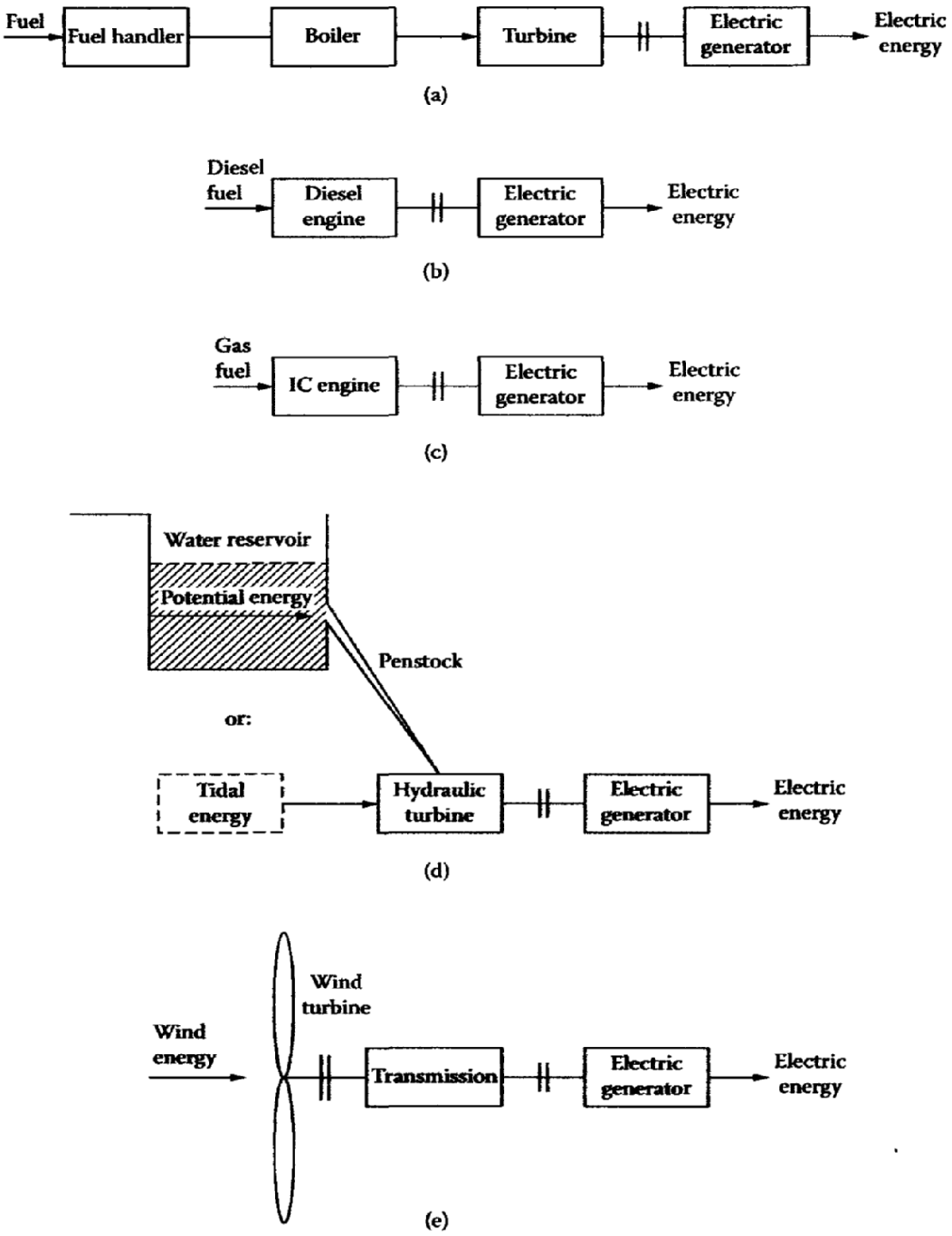


FIGURE 1.5 The most important ways to produce electric energy: (a) fossil fuel thermoelectric energy conversion, (b) diesel-engine electric generator, (c) IC engine electric generator, (d) hydro turbine electric generator, and (e) wind turbine electric generator.

Types of Power Plants

Types of Electric Power plants

A **power plant** (also referred to as **generating station** or **power station**) is a facility for the generation of electric power. At the center of nearly all power stations is a generator, which is an electromechanical device that converts mechanical energy into electrical energy by creating relative motion between a magnetic field and a conductor. The energy source harnessed to turn the generator varies widely. It depends chiefly on what fuels are easily available and the types of technology that the power company has access to.

1. Thermal power plants

In thermal power plants, mechanical power is produced by a heat engine, which transforms thermal energy, often from combustion of a fuel, into rotational energy. Most thermal power plants produce steam, and these are sometimes called steam power stations. About 86% of all electric power is generated by use of steam turbine. Not all thermal energy can be transformed to mechanical power, according to the second law of thermodynamics. Therefore, there is always heat lost to the environment. If this loss is employed as useful heat, for industrial processes or district heating, the power plant is referred to as a **cogeneration** power plant or CHP (combined heat-and-power) plant. In countries where district heating is common, there are dedicated heat plants called heat-only boiler stations. An important class of power stations in the Middle East uses byproduct heat for desalination of water.

Classification

Thermal power plants are classified by the type of fuel and the type of prime mover installed.

(1). By fuel

- Fossil fuelled power plants:

  – Coal – Fired power plants

  - Oil – fired power plants

- Natural Gas – Fired power plants

- Nuclear power plants use a nuclear reactor's heat to operate a steam turbine generator.
- Geothermal power plants use steam extracted from hot underground rocks.

(2). By prime mover

- Steam turbine plants use the dynamic pressure generated by expanding steam to turn the blades of a turbine.
- Gas turbine plants use the dynamic pressure from flowing gases to directly operate the turbine. Natural-gas fuelled turbine plants can start rapidly and so are used to supply "peak" energy during periods of high demand, though at higher cost than base-loaded plants.
- Combined cycle plants have both a gas turbine fired by natural gas, and a steam boiler and steam turbine which use the exhaust gas from the gas turbine to produce electricity. This greatly increases the overall efficiency of the plant, and most new baseload power plants are combined cycle plants fired by natural gas.
- Diesel Engine Power Plants : Diesels are internal combustion reciprocating engines are used to provide power for isolated communities and are frequently used for small cogeneration plants. Hospitals, office buildings, industrial plants, and other critical facilities also use them to provide backup power in case of a power outage. These are usually fuelled by diesel oil, and heavy oil.

2. Other sources of energy

Other power stations use renewable energy from wave or tidal motion, wind, sunlight or the energy of falling water, hydroelectricity.

2.1 Hydroelectric Plants

The oldest form of energy conversion is by the use of water power. In the hydroelectric plant the energy is obtained free of cost. This attractive feature has always been somewhat offset by the very high capital cost of construction, especially of the civil engineering works. Today, however, the capital cost per kilowatt of small hydroelectric stations is becoming comparable with that of steam stations. Hydroelectric dams impound a reservoir of water and release it through one or more water turbines to generate electricity.

2.2 Pumped storage plants

A pumped storage hydroelectric power plant is a net consumer of energy but decreases the price of electricity. Water is pumped to a high reservoir during the night when the demand, and price, for electricity is low. During hours of peak demand, when the price of electricity is high, the stored water is released to produce electric power. Some pumped storage plants are actually not net consumers of electricity because they release some of the water from the lower reservoir downstream, either continuously or in bursts.

2.3 Solar

A solar photovoltaic power plant converts sunlight into electrical energy, which may need conversion to alternating current for transmission to users. This type of plant does not use rotating machines for energy conversion. Solar thermal electric plants are another type of solar power plant. They direct sunlight using either parabolic troughs or heliostats. Parabolic troughs direct sunlight onto a pipe containing a heat transfer fluid, such as oil, which is then used to boil water, which turns the generator. The central tower type of power plant uses hundreds or thousands of mirrors, depending on size, to direct sunlight onto a receiver on top of a tower. Again, the heat is used to produce steam to turn turbines. There is yet another type of solar thermal electric plant. The sunlight strikes the bottom of the pond, warming the lowest layer which is prevented from rising by a salt gradient. A Rankine cycle engine exploits the temperature difference in the layers to produce electricity.

2.4 Wind

Wind turbines can be used to generate electricity in areas with strong, steady winds. Many different designs have been used in the past, but almost all modern turbines being produced today use the Dutch six-bladed, upwind design. Grid-connected wind turbines now being built are much larger than the units installed during the 1970s, and so produce power more cheaply and reliably than earlier models. With larger turbines (on the order of one megawatt), the blades move more slowly than older, smaller, units, which makes them less visually distracting and safer for airborne animals.

2.5 Fossil fuelled power plants:

2.5.1 Steam Generation

The combustion of coal, oil or gas in boilers produces steam, at high temperature and high pressure .The steam so produced is used in driving the steam turbines coupled to the generators and thus generating the electric power.

Oil has economic advantages when it can be pumped directly from the refinery through pipe lines direct to the boilers of the power plant.

Gas obtained directly from extraction platforms is becoming very useful.

The energy from nuclear fission can also provide energy to produce steam for turbines.

The steam power-station operates on the Rankine cycle, modified to include superheating, feed-water heating, and steam reheating. Thermal efficiency results from the use of steam at the highest possible pressure and temperature.

Also, for turbines to be economically constructed, the larger the size the less the capital cost. As a result, turbogenerator sets of 500 MW and more have been used. With steam turbines of 100 MW capacity and more, the efficiency is increased by reheating the steam, using an external heater, after it has been partially expanded. The reheated steam is then returned to the turbine where it is expanded through the final stages of blading. A schematic diagram of a coal-fired station is shown in Figure(A). In Figure (B)the flow of energy in a modern steam station is shown.

Constituents of Steam Power Plants

The important parts and auxiliaries of steam power plant are:

1. Steam generating equipment

In coal-fired stations, Figure (A), coal is conveyed to a mill and crushed into fine powder, i.e. pulverized. The pulverized fuel is blown into the boiler where it mixes with a supply of air for combustion. The steam generating equipment are:

(a)Boiler

(b) Boiler Furnaces

(c) Superheaters and reheaters

(i) Radiant superheaters

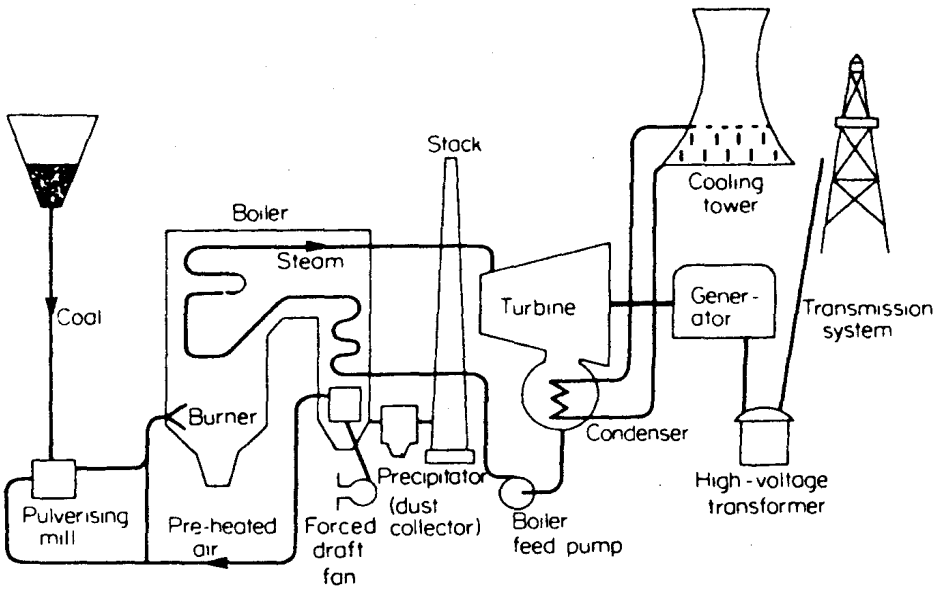


Figure (A) Schematic view of coal-fired generating station

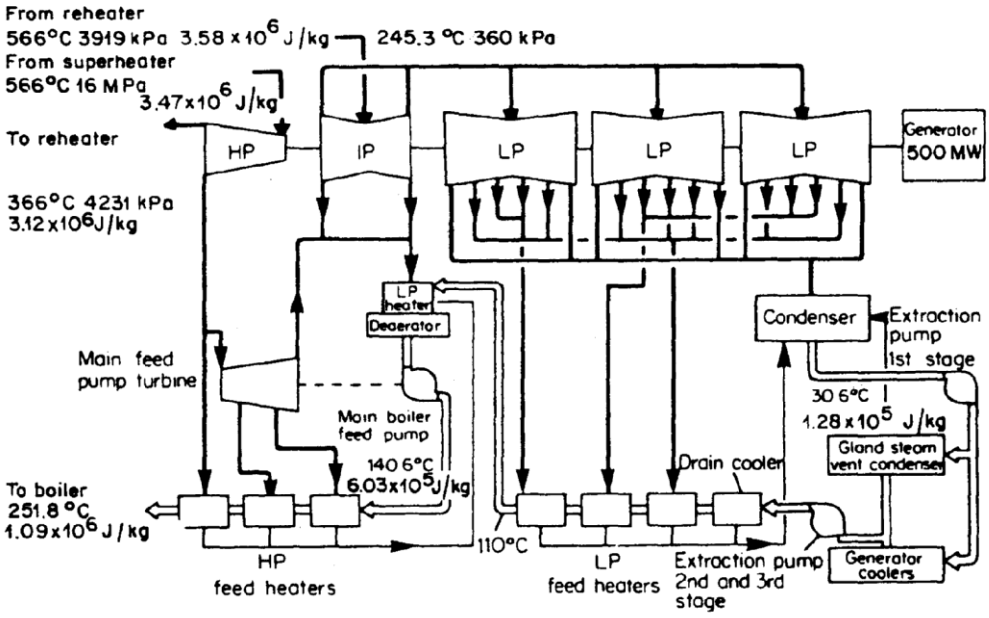


Figure (B) Energy flow diagram for a 500MW turbogenerator

(ii) Convection superheaters

(d) Economizer and air pre-heater (recover part of heat to raise boiler efficiency).

Despite continual advances in the design of boilers and in the development of improved materials, the nature of the steam cycle is such that efficiencies are comparatively low and vast quantities of heat are lost in the condensate and atmosphere. However, the great advances in design and materials in the last few years have increased the thermal efficiencies of coal stations to about 40 per cent.

2.Condensors

The exhaust from the L.P. (low pressure) turbine, Figure (A), is cooled to form condensate by the passage through the condenser of large quantities of sea- or river-water. Where this is not possible, cooling towers are used.

3. Cooling Towers

Because of the fundamental limits to thermodynamic efficiency of any heat engine, all thermal power plants produce waste heat as a byproduct of the useful electrical energy produced. Natural draft wet cooling towers at nuclear power plants and at some large thermal power plants are large hyperbolic chimney-like structures that release the waste heat to the ambient atmosphere by the evaporation of water .

However, the mechanical induced-draft or forced-draft wet cooling towers in many large thermal power plants, petroleum refineries, petrochemical plants, geothermal, biomass and waste to energy plants use fans to provide air movement upward through downcoming water and are not hyperbolic chimney-like structures. The induced or forced-draft cooling towers are rectangular, box-like structures filled with a material that enhances the contacting of the upflowing air and the downflowing water.

In desert areas a dry cooling tower or radiator may be necessary, since the cost of make-up water for evaporative cooling would be prohibitive. These have lower efficiency and higher energy consumption in fans than a wet, evaporative cooling tower.Where economically and environmentally possible, electric companies prefer to use cooling water from the ocean, or a lake or river, or a cooling pond, instead of a cooling tower. This type of cooling can save the cost of a cooling tower and may have lower energy costs for pumping cooling water through the plant's heat exchangers.

4. Prime-mover (a) Turbines , (b) Reciprocating engine .

5.Water Treatment Chamber

6. Control Room

7. Switchyard (substation)

2.5.2 Steam Turbines

A rotor of a modern **steam turbine**, used in a power plant

A **turbine** is a rotary engine that extracts energy from a fluid flow. The simplest turbines have one moving part, a rotor assembly, which is a shaft with blades attached. Moving fluid acts on the blades, or the blades react to the flow, so that they rotate and impart energy to the rotor. Early turbine examples are windmills and water wheels.

A **steam turbine** is a mechanical device that extracts thermal energy from pressurized steam, and converts it into useful mechanical work. It is particularly suited for use driving an electrical generator — about 86% of all electric generation in the world is by use of steam turbines. The steam turbine is a form of heat engine that derives much of its improvement in thermodynamic efficiency from the use of multiple stages in the expansion of the steam which results in a closer approach to the ideal reversible process.

Types of steam turbines

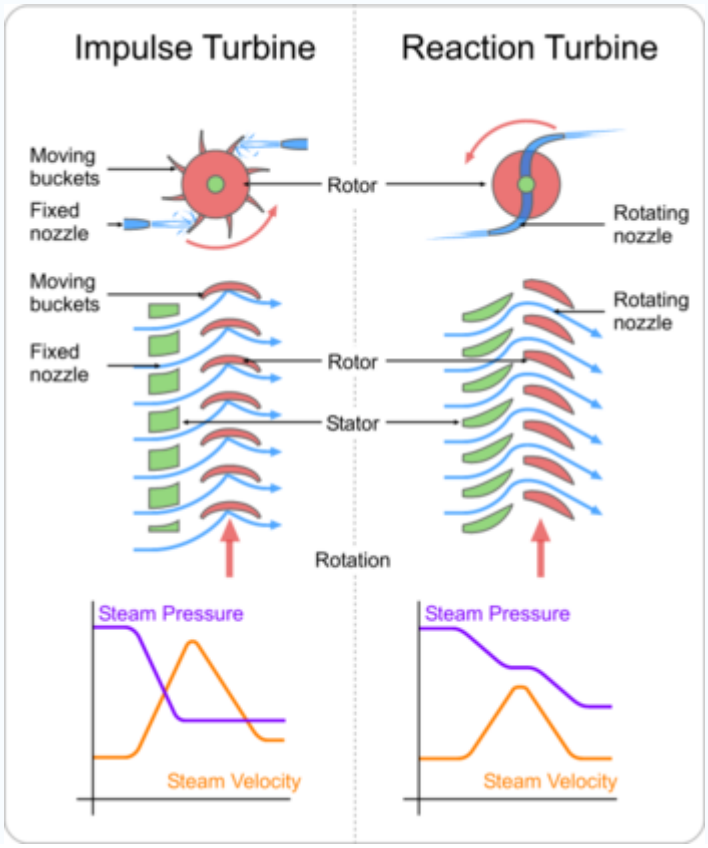
Types of steam turbines include condensing, noncondensing, reheat, extraction and induction .Condensing turbines are most commonly found in electrical power plants. These turbines exhaust steam in a partially condensed state, typically of a quality near 90%, at a pressure well below atmospheric to a condenser.

Reheat turbines are also used almost exclusively in electrical power plants. In a reheat turbine, steam flow exits from a high pressure section of the turbine and is returned to the boiler where additional superheat is added. The steam then goes back into an intermediate pressure section of the turbine and continues its expansion.

Extracting turbines are common in all applications. In an extracting turbine, steam is released from various stages of the turbine, and used for industrial process needs or sent to boiler feedwater heaters to improve overall cycle efficiency. Extraction flows may be controlled with a valve, or left uncontrolled.

Induction turbines introduce low pressure steam at an intermediate stage to produce additional power.

Theory of operation



A working fluid contains potential energy (pressure head) and kinetic energy (velocity head). The fluid may be compressible or incompressible. Several physical principles are employed by turbines to collect this energy:

Impulse turbines

These turbines change the direction of flow of a high velocity fluid jet. The resulting impulse spins the turbine and leaves the fluid flow with diminished kinetic energy. There is no pressure change of the fluid in the turbine rotor blades. Before reaching the turbine the fluid's *Pressure head* is changed to *velocity head* by accelerating the fluid with a nozzle. Pelton wheels and de Laval turbines use this process exclusively.

The types of impulse turbines are:

- **Banki turbine**
- **Girard turbine**
- **Jonal turbine**
- **Pelton turbine**
- **Turgo turbine**

Reaction turbines

These turbines develop torque by reacting to the fluid's pressure or weight. The pressure of the fluid changes as it passes through the turbine rotor blades. Francis turbines and most steam turbines use this concept.

The reaction turbines are:

- **Fourneyron turbine**
- **Francis turbine**
- **Thompson turbine**
- **Kaplan turbine**
- **Propeller turbine**

STEAM POWER PLANTS

THE RANKINE CYCLE

The Rankine cycle is the most widely used cycle for electric power generation. Figure 2.1 illustrates a simplified flow diagram of a Rankine cycle. Figure 2.2(*a*, *b*) shows the ideal Rankine cycle on *P*-*v* and *T*-*s* diagrams. Cycle 1-2-3-4-*B*-1 is a saturated Rankine cycle (saturated vapor enters the turbine). Cycle 1′-2′-3-4-*B*-1′ is superheated Rankine cycle.

The cycles shown are internally reversible. The processes through the turbine and pump are adiabatic reversible. Hence, vertical on the *T*-*s* diagram. There are no pressure losses in the piping. Line 4-*B*-1-1′ is a constant-pressure line.The reversible Rankine cycle has the following processes:

Line 1-2 or 1′-2′. Adiabatic reversible expansion through the *turbine.* The exhaust vapor at point 2 or point 2′ is usually in the two-phase region.

Line 2-3 or 2′-3. Constant-temperature and, being a two-phase mixture process, constant-pressure heat rejection in the condenser.

Line 3-4. Adiabatic reversible compression by the *pump* of saturated liquid at the condenser pressure, point 3, to subcooled liquid at the steam generator pressure, point 4. Line 3-4 is vertical on both the *P*-*v* and *T*-*s* diagrams because the liquid is essentially Income pressible and the pump is adiabatic reversible.

Line 4-1 or 4-1′. Constant-pressure heat addition in the *steam generator.* Line 4-*B*-1-1′ is a constant-pressure line on both diagrams. Portion 4-*B* represents bringing the subcooled liquid, point 4, to saturated liquid at point *B.* Section 4-*B* in the steam generator is called an *economizer*. Portion *B*-1 represents heating the saturated liquid to saturated vapor at constant pressure and temperature (being a two-phase mixture), and section *B*-1 in the steam generator is called the *boiler* or *evaporator.* Portion 1-1′, in the superheat cycle, represents heating the saturated vapor at point 1 to point 1′. Section 1-1′ in the steam generator is called a *superheater.*

Following is the thermodynamic analysis based on a unit mass of vapor in the cycle:

Heat added

$$q_A = h_1 - h_4 \quad \text{Btu/lb}_m \text{ (or J/kg)} \tag{2.1}$$

Turbine work

$$w_T = h_1 - h_2 \quad \text{Btu/lb}_m \text{ (or J/kg)} \tag{2.2}$$

Heat rejected

$$|q_R| = h_2 - h_3 \quad \text{Btu/lb}_m \text{ (or J/kg)} \tag{2.3}$$

Pump work

$$|w_p| = h_4 - h_3 \tag{2.4}$$

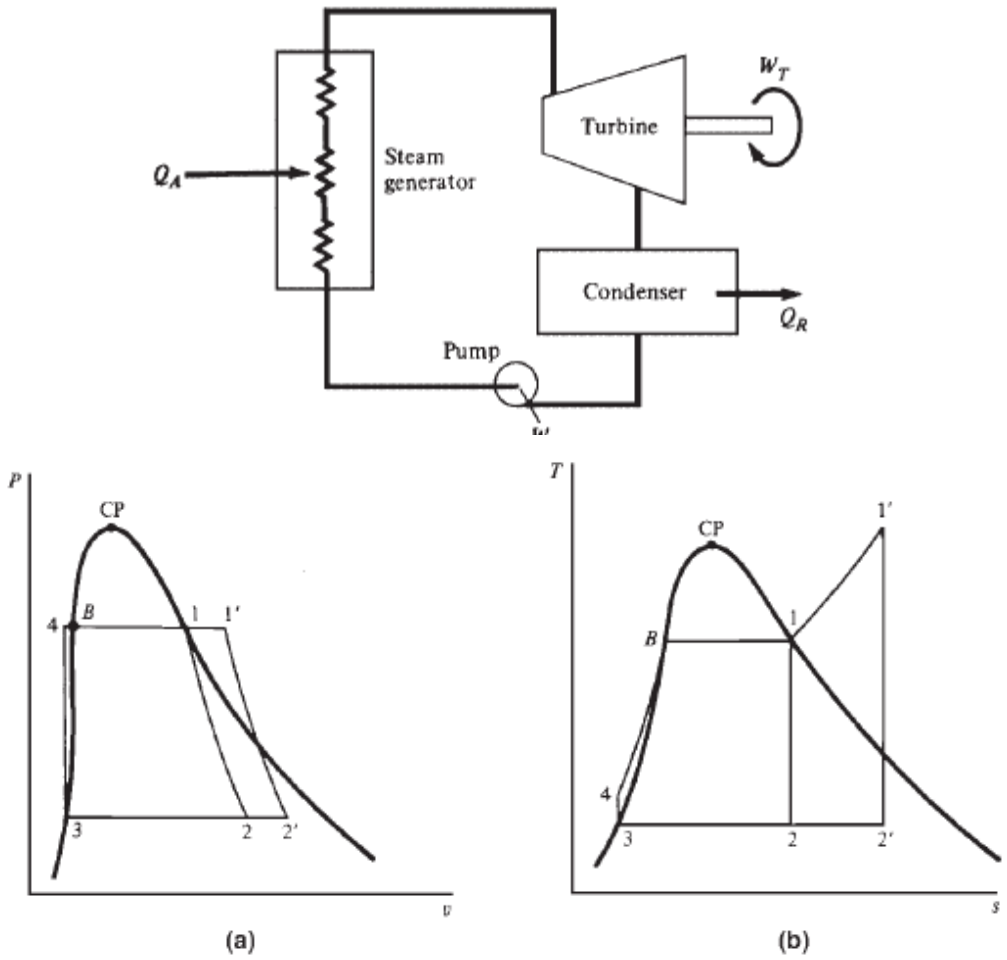


FIGURE 2.2 Ideal Rankine cycles of the (*a*) *P-V* and (*b*) *T-s* diagrams. Line 1-2-3-4-*B*-1 = saturated cycle. Line 1′-2′-3-4-*B*-1′ = superheated cycle. CP = critical point.

Net work

$$\Delta w_{\text{net}} = (h_1 - h_2) - (h_4 - h_3) \quad \text{Btu/lb}_\text{m} \text{ (or J/kg)} \tag{2.5}$$

Thermal efficiency

$$\eta_{\text{th}} = \frac{\Delta w_{\text{net}}}{q_A} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)} \tag{2.6}$$

For small units where P_4 is not much larger than P_3,

$$h_3 \approx h_4 \tag{2.7}$$

The pump work is negligible compared with the turbine work, the thermal efficiency (with little error) is

$$\eta_{th} = \frac{h_1 - h_2}{h_1 - h_3} \tag{2.8}$$

This assumption is not true for modern power plants, where *P*4 is 1000 psi (70 bar) or higher, while *P*3 is about 1 psi (0.07 bar). In this case, the pump work may be obtained by finding *h*3 as the saturated enthalpy of liquid at *P*3 from the steam tables. One can find *h*4 from the subcooled liquid tables at *T*4 and *P*4 (assuming that *T*3 _ *T*4). An approximation for the pump work may be obtained from the change in flow work:

$$\boldsymbol{wp = v3\ (P4 - P3)} \tag{2.9}$$

REHEAT

Reheat improves the cycle efficiency. Figures 2.3 and 2.4 illustrate the flow and *T*-*s* diagrams of an internally reversible Rankine cycle (i.e., the process through the turbine and pump is adiabatic and reversible. Also, there is no pressure drop in the cycle). The cycle superheats and reheats the vapor. The vapor in the reheat cycle at point 1 is expanded in the high-pressure turbine to point 2.

Note: Line *ab* represents the primary coolant in a counterflow steam generator (the primary heat source is the combustion gases from the steam generator furnace).

The vapor is returned back to the steam generator where it is reheated at constant pressure (ideally) to a temperature near that at point 1. The reheated steam now enters the low-pressure turbine where it expands to the condenser pressure.

In a reheat cycle, heat is added twice: from point 6 to point 1 and from point 2 to point 3. It keeps the boiler-superheat-reheat portion from point 7 to point 3 close to the primary fluid line *ae.* This increases the cycle efficiency.

Reheat also produces drier steam at the turbine exhaust (point 4 instead of point 4′).

Modern fossil-fueled power plants have at least one stage of reheat. If more than two stages of reheat are used, cycle complication occurs and the improvement in efficiency does not justify the increase in capital cost.

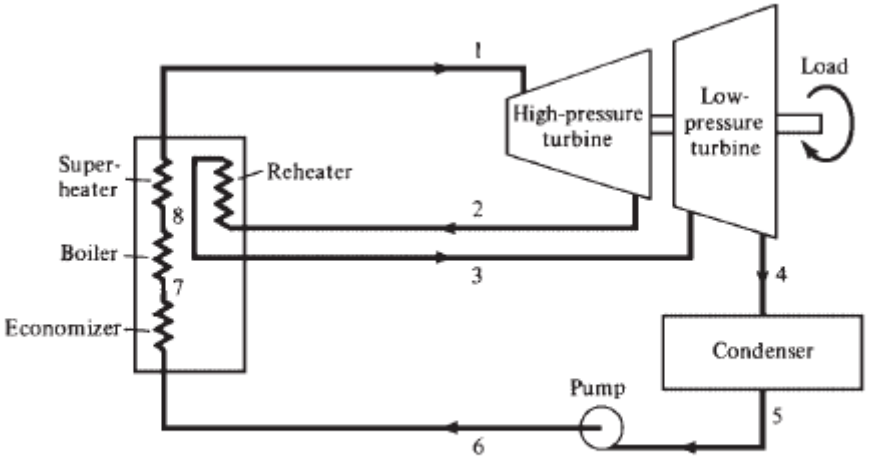


FIGURE 2.3 Schematic of a Rankine cycle with superheat and reheat.

In some plants, the steam is not reheated in the steam generator. It is reheated in a separate heat exchanger ***reheater***. A portion of the steam at point 1 is used to reheat the steam at point 2. This flow condenses and is sent to the feed water heaters. The reheat cycle involves two turbine work terms and two heat addition terms. (Refer to Fig. 2.4.).

$$W_T = (h_1 - h_2) + (h_3 - h_4) \tag{2.10}$$

$$|W_p| = h_6 - h_5 \tag{2.11}$$

$$\Delta W_{\text{net}} = (h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5) \tag{2.12}$$

$$q_A = (h_1 - h_6) + (h_3 - h_2) \tag{2.13}$$

$$\eta_{\text{th}} = \frac{\Delta W_{\text{net}}}{q_A} \tag{2.14}$$

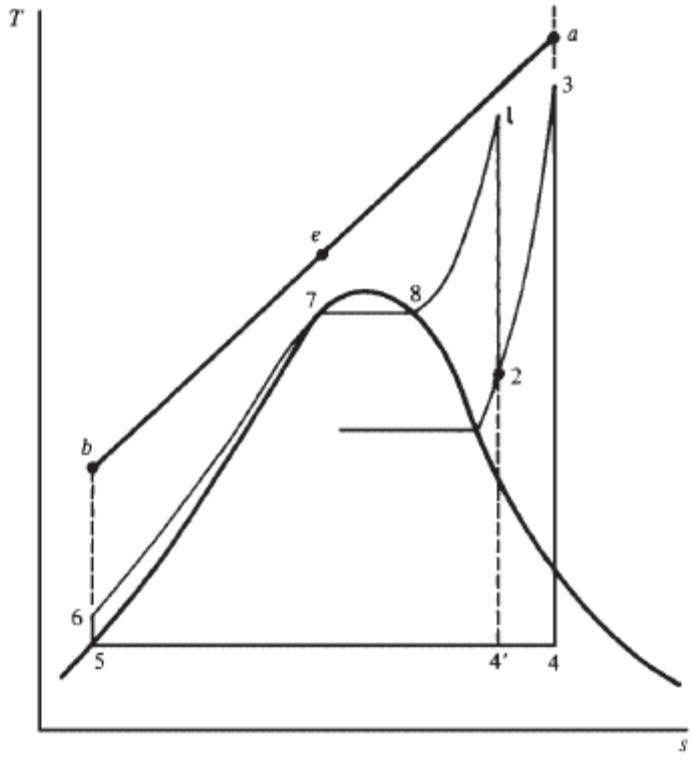


FIGURE 2.4 *T-s* diagram of Rankine cycle of Fig. 2.3.

The reheat pressure *P*2 affects the cycle efficiency. Figure 2.5 illustrates the variation in cycle efficiency as a function of the ratio of reheat pressure to initial pressure *P*2/*P*1. *P*1 = 2500 psia, *T*1 = 1000°F, and *T*3 =1000°F. If the reheat pressure is too close to the initial pressure, the increase in cycle efficiency is minimal because only a small portion of heat is added at high temperature.

The optimum reheat efficiency is reached when *P*2/*P*1 is between 20 and 25 percent. Lowering the reheat pressure, *P*2 further causes the efficiency to decrease again (area 2-3- 4-4′ decreases if *P*2 drops below 0.2).

Exhaust steam is drier in a reheat cycle. A superheat-reheat power plant is designated *P*1/*T*1/*T*3 (e.g., 2500 psi/1000°F/1000°F). Table 2.1 compares the performance of five

plants. Note the increase in efficiency due to reheating and the significant drop in efficiency caused by using non ideal fluids.

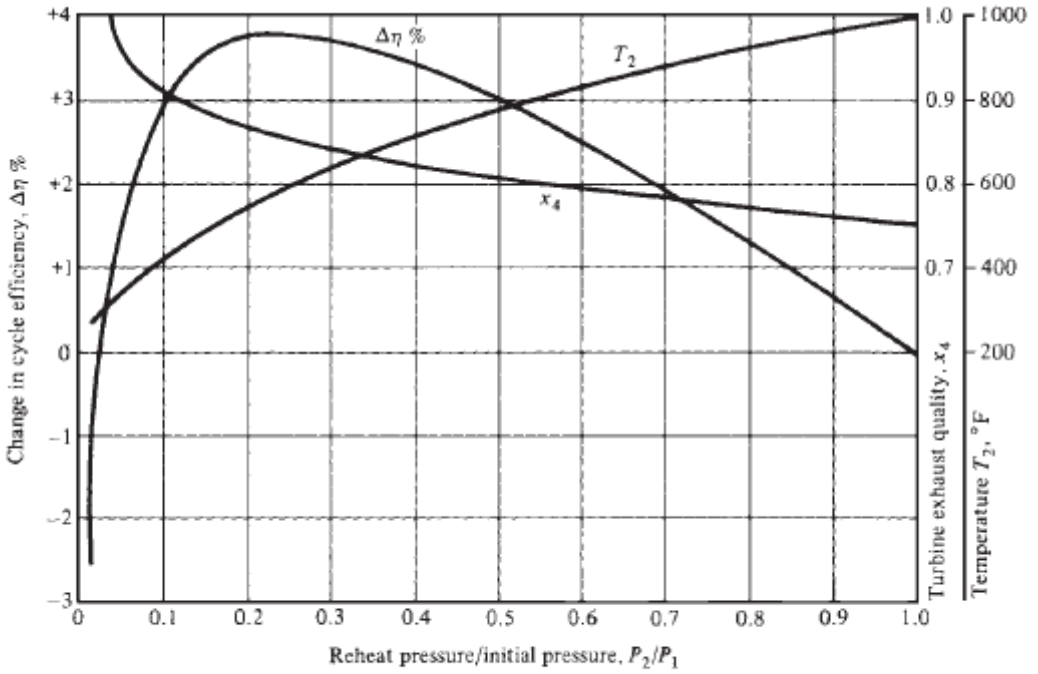


FIGURE 2.5 Effect of reheat-to-initial-pressure ratio on efficiency, high-pressure turbine exit temperature, and low-pressure turbine exit quality. Data for cycle of Fig. 2.7 with initial steam at 2500 psia and 1000°F, and steam reheat to 1000°F (2500/1000/1000).

TABLE 2.1 Steam Power Plant Performance Comparison

	Cycle				
Data	A Superheat 2500/1000	B 2500 saturated	C Superheat 1000/668.11	D 2500/ 1000/1000	E 2500/1000 nonideal
Turbine inlet pressure, psia	2500	2500	1000	2500	2500
Turbine inlet temperature, °F	1000	668.11	668.11	1000	1000
Condenser pressure, psia	1	1	1	1	1
Inlet steam enthalpy, Btu/lb_m	1457.5	1093.3	1303.1	1457.5	1457.5
Exhaust steam enthalpy, Btu/lb_m	852.52	688.36	834.44	970.5	913.02
Turbine work, Btu/lb_m	604.98	404.94	468.66	741.8	544.48
Pump work, Btu/lb_m	7.46	7.46	2.98	7.46	11.52
Net work, Btu/lb_m	597.52	397.48	465.68	734.34	532.96
Heat added, Btu/lb_m	1380.31	1016.11	1230.39	1635.10	1376.25
Exhaust steam quality	0.7555	0.5971	0.7381	0.8694	0.8139
Cycle efficiency, %	43.29	39.12	37.85	44.91	38.73

REGENERATION

External irreversibility is caused by the temperature differences between the primary heatsource (combustion gases or primary coolant) and the working fluid. Temperature differences between condensing working fluid and the heat sink fluid (condenser cooling water or cooling air) also cause external irreversibility.

Figure 2.6 illustrates the working fluid (line 4-*B*-1-2-3-4) in a Rankine cycle. Line *a*-*b* represents the primary coolant in a counter flow steam generator, and line *c*- represents the heat sink fluid in a counter flow heat exchanger. If line *a*-*b* is too close to line 4-*B*-1, the temperature differences between the primary coolant and the working fluid would be small. Therefore, the irreversibilities (caused by heat loss from the primary coolant) are small, but the steam generator is large and costly.

If line *a*-*b* is much higher than line 4*B*-1 (significant temperature differences between the primary coolant and the working fluid), the steam generator would be small and inexpensive, but the overall temperature differences and irreversibilities would be large. Hence, the plant efficiency would be reduced. An examination of Fig. 2.6 reveals that a great deal of irreversibilities occur prior to the point of boiling (i.e., in the economizer section of the steam generator where the temperature differences between line *b*-*a* and line 4-*B*are the greatest of all during the entire heat addition process).

The thermal efficiencies of all types of power plants suffer from this irreversibility, which can be eliminated if the liquid is added to the steam generator at point *B* instead of point 4. The process of *regeneration* achieves this objective by exchanging heat between the expanding fluid in the turbine and the compressed fluid before heat addition.

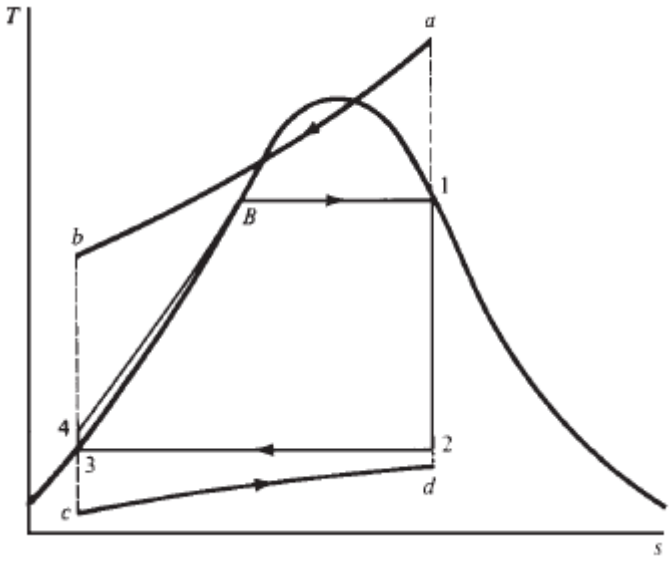


FIGURE 2.6 External irreversibility with Rankine cycle.

FEEDWATER HEATING

Feedwater heating is accomplished by heating the compressed liquid at point 4 in a number of finite steps in heat exchangers ("feedheaters") by steam that is bled from the turbine at selected stages. (See Fig. 2.6.) Modern steam power plants use between five and eight feedwater heating stages. None is built without feedwater heating.

In a regenerative cycle, the liquid enters the steam generator at a point below point *B* (Fig. 2.6). An economizer section (this is the part of the steam generator that heats the incoming fluid between points 4 and B) is still needed. However, it is much smaller than the one that is needed for nonregenerative cycles.

The three types of feedwater heaters include:

1. Open or direct-contact type
2. Closed type with drains cascaded backward
3. Closed type with drains pumped forward

COGENERATION

Cogeneration is the simultaneous generation of electricity and steam (or heat) in a power plant. Cogeneration is recommended for industries and municipalities because it can produce electricity more cheaply and/or more conveniently than a utility. Also, it provides the total energy needs (heat and electricity) for the industry or municipality.

Cogeneration is beneficial if it saves energy when compared with separate generation of electricity and steam (or heat). The cogeneration plant efficiency η_{co} is given by

$$\eta_{co} = \frac{E + \Delta H_s}{Q_A}$$

where E = electric energy generated

ΔHs = heat energy, or heat energy in process steam

=(enthalpy of steam entering the process) - (enthalpy of process condensate returning to plant)

QA = heat added to plant (in coal, nuclear fuel, etc.)

For separate generation of electricity and steam, the heat added per unit of *total* energy output is

$$\frac{e}{\eta_e} + \frac{(1-e)}{\eta_h}$$

where e = electrical fraction of total energy output = [E/ (E+ΔHs)]

ηe =electric plant efficiency

ηh = steam (or heat) generator efficiency
The *combined efficiency* ηc *for separate generation* is therefore given by

$$\eta_c = \frac{1}{(e/\eta_e) + [(1 - e)/\eta_h]}$$

Cogeneration is beneficial if the efficiency of the cogeneration plant [Eq. (2.28)] is greater than that of separate generation [Eq. (2.30)].

Types of Cogeneration
The two main categories of cogeneration are (1) the topping cycle and (2) the bottoming cycle.

The Topping Cycle. In this cycle, the primary heat source is used to generate highenthalpy steam and electricity. Depending on process requirements, process steam at low enthalpy is taken from any of the following:
● Extracted from the turbine at an intermediate stage (like feedwater heating).
● Taken from the turbine exhaust. The turbine in this case is called a *back-pressure turbine.* Process steam requirements vary widely, between 0.5 and 40 bar.

The Bottoming Cycle. In this cycle, the primary heat (high enthalpy) is used directly for process requirements [e.g., for a high-temperature cement kiln (furnace)]. The low enthalpy waste heat is then used to generate electricity at low efficiency.
This cycle has lower combined efficiency than the topping cycle. Thus, it is not very common. Only the topping cycle can provide true savings in primary energy.

Arrangements of Cogeneration Plants
The various arrangements for cogeneration in a topping cycle are as follows:
● Steam-electric power plant with a back-pressure turbine.
● Steam-electric power plant with steam extraction from a condensing turbine (Fig. 2.14).
● Gas turbine power plant with a heat recovery boiler (using the gas turbine exhaust to generate steam).
● Combined steam-gas-turbine cycle power plant. The steam turbine is either of the backpressure type or of the extraction-condensing type.

Economics of Cogeneration
Cogeneration is recommended if the cost of electricity is less than the utility. If a utility is not available, cogeneration becomes necessary, regardless of economics.
The two types of power plant costs are (1) capital costs and (2) production costs.
Capital costs are given in total dollars or as unit capital costs in dollars per kilowatt net. Capital

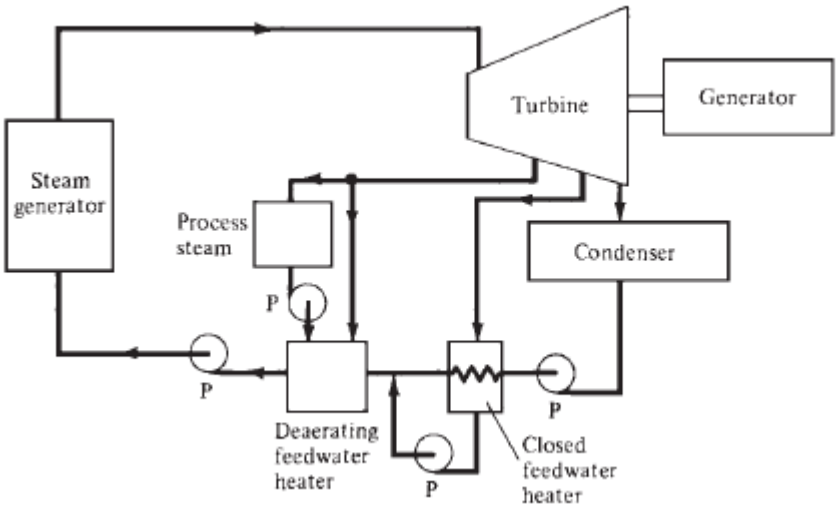


FIGURE 2.14 Schematic of basic cogeneration plant with extraction-condensing turbine.

costs determine if a plant is good enough to obtain financing. Thus, it is able to pay the fixed charges against capital costs.

Production costs are calculated annually, and they are given in mills per kilowatt hour (a *mill* is U.S.$0.001). Production costs are the real measure of the cost of power generated. They are composed of the following:

- Fixed charges against the capital costs
- Fuel costs
- Operation and maintenance costs

All the costs are in mills per kilowatt hour. They are given by

$$\text{Production costs} = \frac{\text{total } (a + b + c)\ \$ \text{ spent per period} \times 10^3}{\text{KWh (net) generated during the same period}}$$

where the period is usually taken as one year.

The plant operating factor (POF) is defined for all plants as

$$\text{POF} = \frac{\text{total net energy generated by plant during a period of time}}{\text{rated net energy capacity of plant during the same period}}$$

STEAM TURBINES AND AUXILIARIES

In a steam turbine, high-enthalpy (high pressure and temperature) steam is expanded in the nozzles (stationary blades) where the kinetic energy is increased at the expense of pressure energy (increase in velocity due to decrease in pressure). The kinetic energy (high velocity) is converted into mechanical energy (rotation of a shaft _ increase of torque or speed) by impulse and reaction principles. The impulse principle consists of changing the momentum ($m\mathbf{V}$) of the flow, which is directed to the moving blades by the stationary blades. The
jet's impulse force pushes the moving blades forward. The reaction principle consists of a reaction force on the moving blades due to acceleration of the flow as a result of decreasing cross-sectional area.

Figure 3.1 illustrates a turbine with impulse blading. It has one velocity-compounded stage (the velocity is absorbed in stages) and four pressure-compounded stages. The velocity is reduced in two steps through the first two rows of moving blades. In the moving blades, velocity decreases while the pressure remains constant.

Figure 3.2 illustrates a reaction turbine. The reaction stages are preceded by an initial velocity-compounded impulse stage where a large pressure drop occurs. This results in a shorter, less expensive turbine. Figure 3.3 illustrates the arrangement of components in a steam power plant.

TURBINE TYPES

Steam turbines up to between 40 and 60 MW rating are usually single-cylinder machines. Larger units use multiple cylinders to extract the energy from the steam.

Single-Cylinder Turbines

The two types of steam turbines are *condensing* and *back-pressure* (noncondensing). Figure 3.4 illustrates these types and some of their sub classifications. Back-pressure turbines exhaust the steam at the pressure required by the process. Automatic extraction turbines allow part of the steam to be withdrawn at an intermediate stage (or stages) while the remainder of the steam is exhausted to a condenser. These turbines require special governors and valves to maintain constant pressure of the extraction steam while the turbine load and extraction demand are varying. Uncontrolled extraction turbines are used to supply steam to feedwater heaters, since the pressure at the extraction points varies with the turbine load.

Many moderate-pressure plants have added high-pressure noncondensing turbines to increase capacity and improve efficiency. High-pressure boilers are added to supply steam to the noncondensing turbines, which are designed to supply the steam to the original turbines. These high-pressure turbines are called *superposed,* or *topping,* units. Mixed-pressure turbines are designed to admit steam at low pressure and expand it to a condenser. These units are used mainly in cogeneration plants.

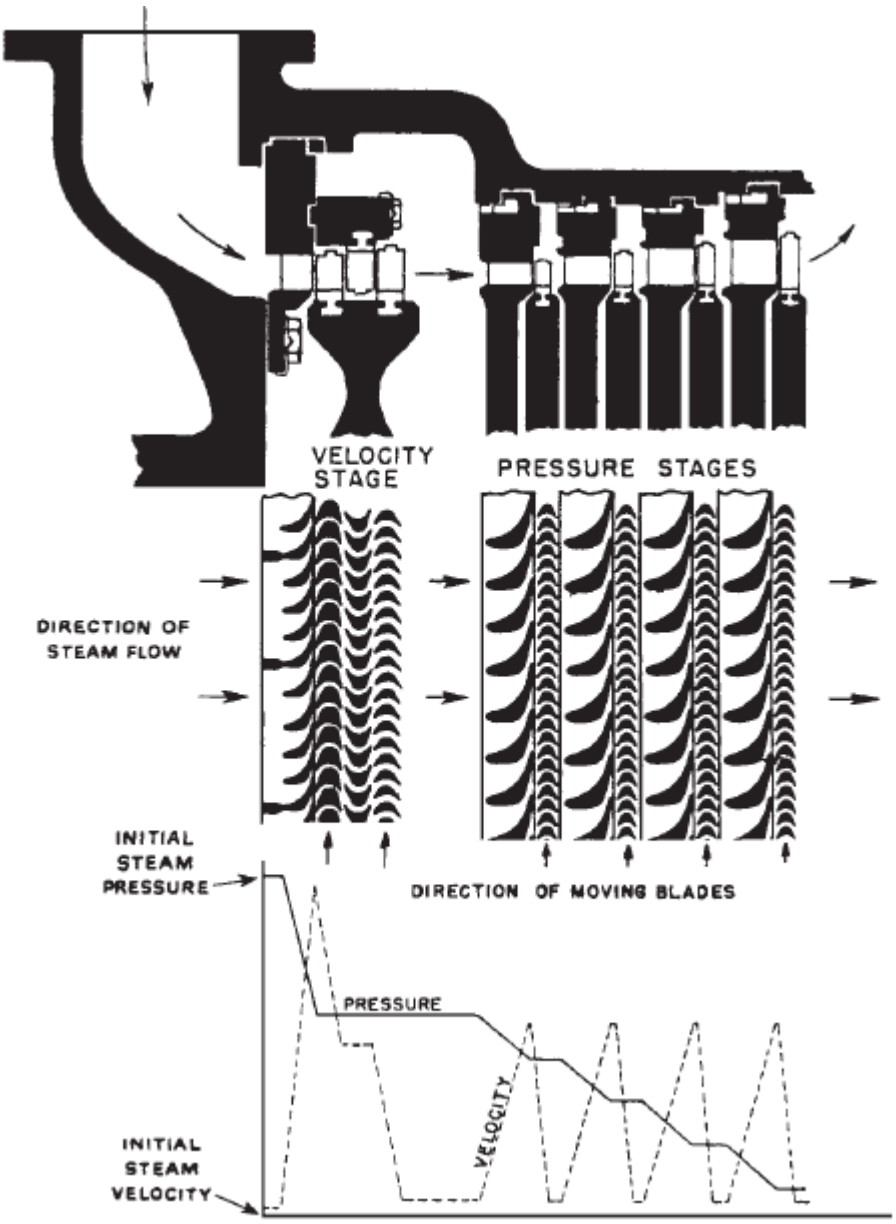


FIGURE 3.1 Turbine with impulse blading. Velocity compounding is accomplished in the first two stages by two rows of moving blades between which is placed a row of stationary blades that reverses the direction of steam flow as it passes from the first to the second row of moving blades. Other ways of accomplishing velocity compounding involve redirecting the steam jets so that they strike the same row of blades several times with progressively decreasing velocity.

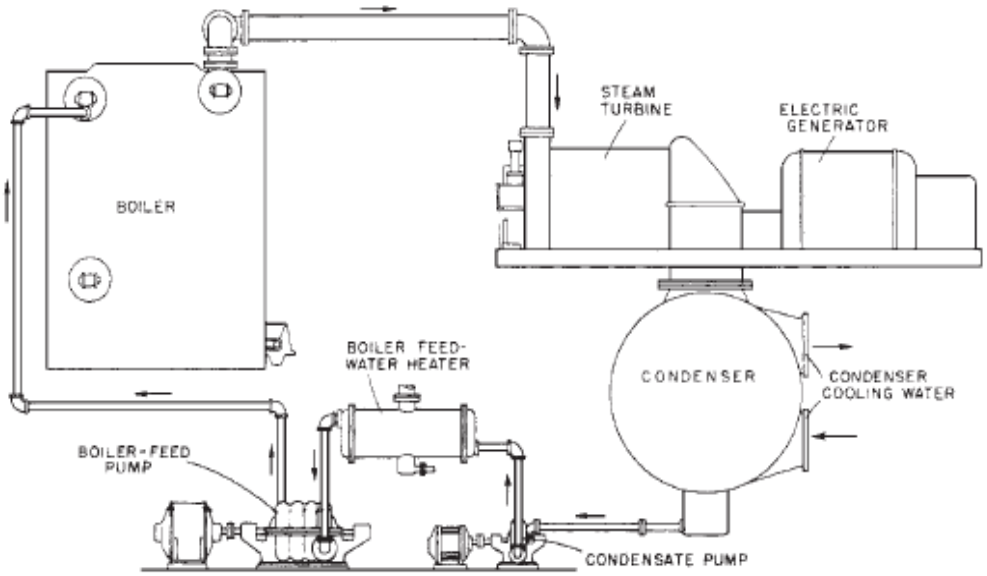


FIGURE 3.3 Simple power plant cycle. This diagram shows that the working fluid, steam and water, travels a closed loop in the typical power plant cycle.

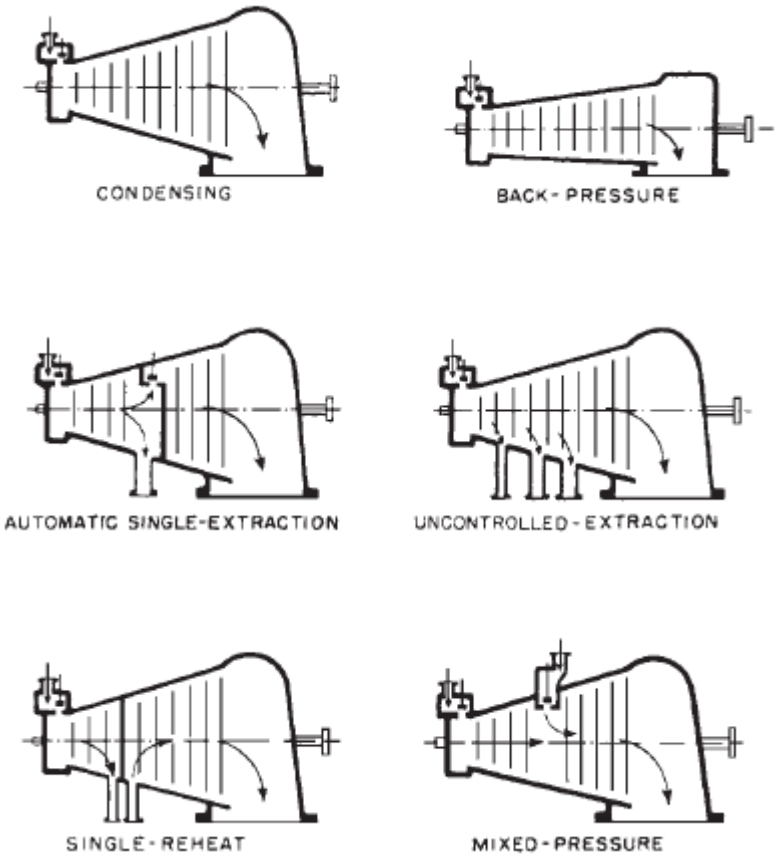


FIGURE 3.4 Single-cylinder turbine types. Typical types of single-cylinder turbines are illustrated. As shown, condensing turbines, as compared to back-pressure turbines, must increase more in size toward the exhaust end to handle the larger volume of low-pressure steam.

Compound Turbines

Compound turbines have more than one cylinder: a high-pressure and a low-pressure turbine. The low-pressure cylinder is usually of the double-flow type to handle large volumes of low-pressure steam (due to limitations on the length of the blades). Large plants may have an intermediate pressure cylinder and up to four low-pressure cylinders. The cylinders can be mounted along a single shaft (tandem-compound), or in parallel groups with two or more shafts (cross-compound). Reheating is usually done between the high- and intermediate-pressure turbines. Figure 3.5 illustrates some of these arrangements.

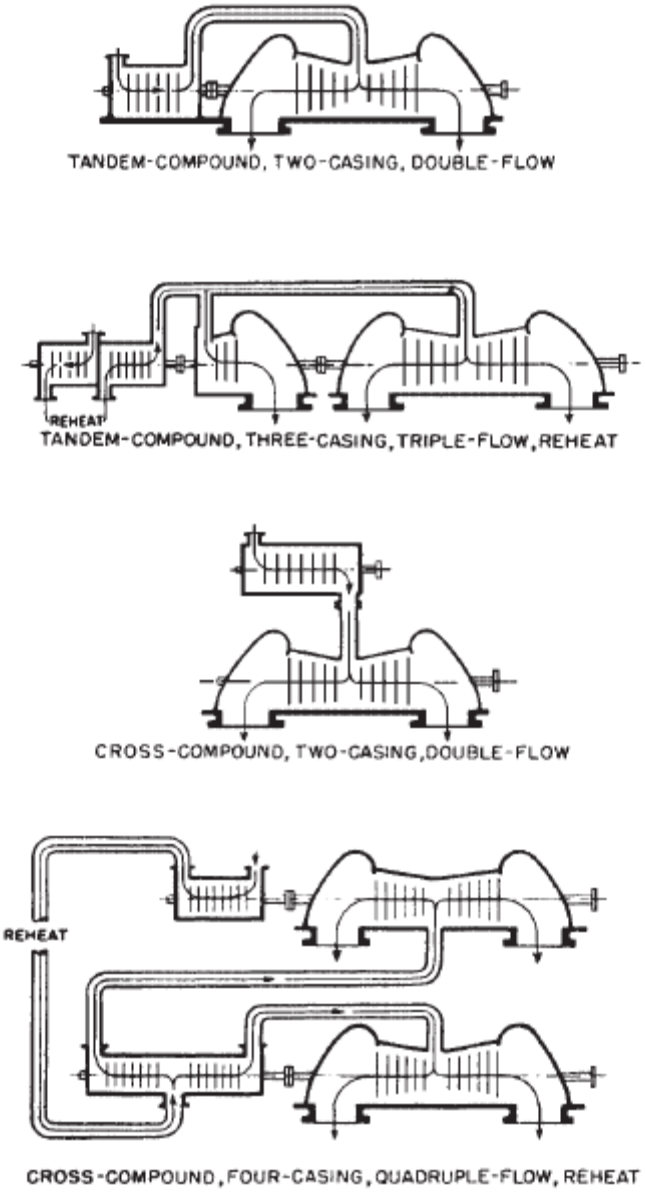


FIGURE 3.5 Some arrangements of compound turbines. While many arrangements are used, these diagrams illustrate some of the more common ones.

Calorific or Heat Values of Fossil Fuels

The amount of heat produced by complete combustion of unit quantity (weight or volume) of fossil fuel is called ***calorific or heat value of fuel*** . It is expressed in k.cals /kg. for solid and liquid fuels and k.cals/liter for gaseous fuel.

Coal	6670 kcal/kg	27.915MJ/kg	1200 Btu/lb
Oil	10,447 kcal/kg	43.733 MJ/ kg	18800 Btu/lb
Gas	9344kcal/m^3	39.11 MJ/ m^3	1050 Btu/1000 ft^3

Note : 1 cal = 4.186 Joules

EFFICIENCY AND HEAT RATE

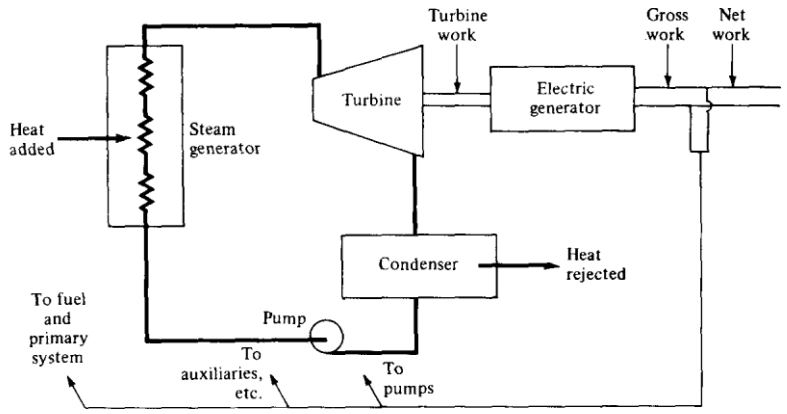
1. EFFICIENCY

In the thermodynamic analysis of cycles and power plants, the **thermal efficiency** and the power output are of prime importance.

The **thermal efficiency** is the ratio of the net work to the heat added to the cycle or power plant. The thermal efficiencies of power plants are less than those computed for cycles as above because the analyses above failed to take into account the various auxiliaries used in a power plant and the various irreversibilities associated with them. A complete analysis of a power plant must take into account all these auxiliaries, the nonidealities in turbines, pumps, friction, heat transfer, throttling, etc., as well as the differences between full-load and partial-load operation.

The **gross efficiency** is the one calculated based on the gross work or power of the turbine-generator. This is the work or power, MW gross, produced before power is tapped for the internal functioning of the power plant, such as that needed to operate pumps, compressors, fuel-handling equipment, and other auxiliaries, labs, computers, heating systems, lighting, etc.(Fig. 2-21).

The **net efficiency** is calculated based on the net work or power of the plant, i.e., the



gross power minus the tapped power above, or the power leaving at the station bus bar.Power plant designers and operators are interested in efficiency as a measure of the economy of the power plant because it affects capital, fuel, and operating costs.

HEAT RATE

Power plant designers and operators use another parameter that more readily reflects the fuel economies. That parameter is called a **heat rate (HR)**. **It is the ratio of the total heat input, usually in MJ/h or Btu/h, to the net electric power generated by the unit, usually in killowatt (kW**). Heat rate thus has the units **Btu/kWh.** The HR is inversely proportional to the efficiency, and hence the lower its value, the better. There are various heat rates corresponding to the work used in the denominator. For example

$$\text{Net cycle HR} = \frac{\text{heat added to cycle, Btu}}{\text{net cycle work kWh}}$$

$$= \frac{\text{rate of heat added to cycle, Btu/h}}{\text{net cycle power, kW}}$$

$$\text{Gross cycle HR} = \frac{\text{rate of heat added to cycle, Btu/h}}{\text{turbine power output, kW}}$$

$$\text{Net station HR} = \frac{\text{rate of heat added to steam generator, Btu/h}}{\text{net station power, kW}}$$

$$\text{Gross station HR} = \frac{\text{rate of heat added to steam generator, Btu/h}}{\text{gross turbine-generator power, kW}}$$

and there are as many thermal efficiencies as there are heat rates.
Because 1 kWh = 3412 Btu, the heat rate of any kind is related to the corresponding thermal efficiency by

$$HR = \frac{3412}{\eta_{th}}$$

Example : A coal-fired power plant has a turbine-generator rated at 1000 MW gross. The plant requires about 9 percent of this power for its internal operations. It uses 9800 tons of coal per day. This coal has a heating value of 11,500 Btu/ lbm, and the steam generator efficiency is 86 percent. Calculate the gross station, net station, and the net steam cycle heat rates .

SOLUTION

$$\text{Rate of coal burned} = 9800 \times \frac{2000}{24} = 816{,}667 \ \text{lb}_m/\text{h}$$

$$\text{Gross station HR} = \frac{816{,}667 \times 11{,}500}{1000 \times 1000} = 9391.67 \ \text{Btu/kWh}$$

$$\text{Station net power output} = (1 - 0.9) \times 1000 = 910 \ \text{MW}$$

$$\text{Net station HR} = \frac{816{,}667 \times 11{,}500}{910 \times 1000} = 10{,}320.5 \ \text{Btu/kWh}$$

$$\text{Heat added to steam generator} = 816{,}667 \times 11{,}500 \times 0.86$$

$$= 8.07683 \times 10^9 \ \text{Btu/h}$$

$$\text{Net steam cycle HR} = \frac{8.07683 \times 10^9}{0.91 \times 10^6} = 8875.64 \ \text{Btu/kWh}$$

The corresponding thermal efficiencies are

$$\text{Gross station efficiency} = \frac{3412}{9391.67} = 36.33\%$$

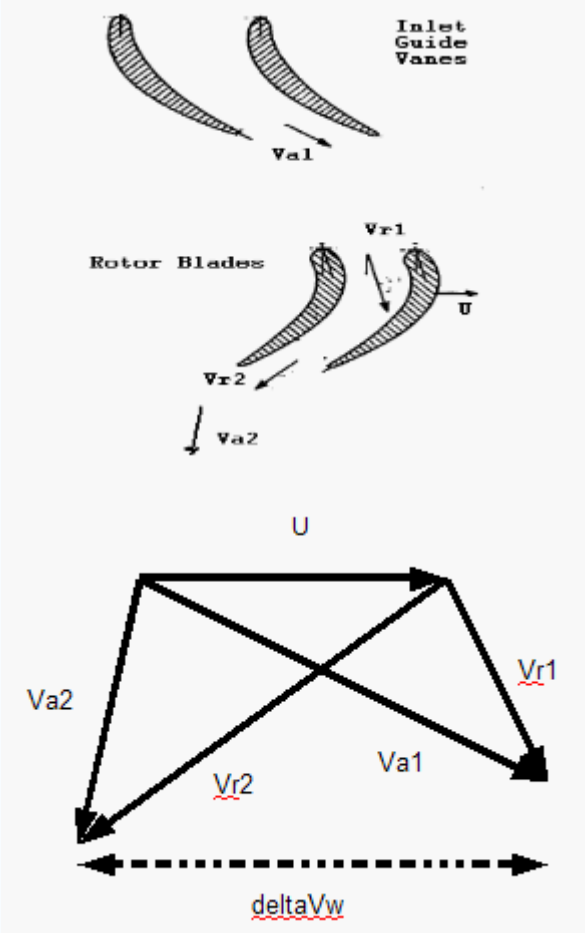
$$\text{Net station efficiency} = \frac{3412}{10{,}320.5} = 33.06\%$$

$$\text{Net cycle efficiency} = \frac{3412}{8875.64} = 38.44\%$$

STEAM TURBINE DESIGN

Classical turbine design methods were developed in the mid 19th century. Vector analysis related the fluid flow with turbine shape and rotation. Graphical calculation methods were used at first. Formulas for the basic dimensions of turbine parts are well documented and a highly efficient machine can be reliably designed for any fluid flow condition. Some of the calculations are empirical or 'rule of thumb' formulae and others are based on classical mechanics. As with most engineering calculations, simplifying assumptions were made.

Velocity triangles can be used to calculate the basic performance of a turbine stage. Gas exits the stationary turbine nozzle guide vanes at absolute velocity Va1. The rotor rotates at velocity U. Relative to the rotor; the velocity of the gas as it impinges on the rotor entrance is Vr1. The gas is turned by the rotor and exits, relative to the rotor, at velocity Vr2. However, in absolute terms the rotor exit velocity is Va2. The velocity triangles are constructed using these various velocity vectors. Velocity triangles can be constructed at any section through the balding (for example: hub , tip, midsection and so on) but are usually shown at the mean stage radius. Mean performance for the stage can be calculated from the velocity triangles, at this radius, using the Euler equation:



Typical velocity triangles for a single turbine stage

$$\Delta H = U \cdot \Delta Vw/g$$

Whence:

$$\left(\frac{\Delta H}{T}\right) = \left(\frac{U}{\sqrt{T}}\right) \cdot \left(\frac{\Delta Vw}{g \cdot \sqrt{T}}\right)$$

where:

g = acceleration of gravity

ΔH = enthalpy drop across stage

T = turbine entry total (or stagnation) temperature

U = turbine rotor peripheral velocity

ΔVw = delta whirl velocity

The turbine pressure ratio is a function of $\left(\frac{\Delta H}{T}\right)$ and the turbine efficiency.

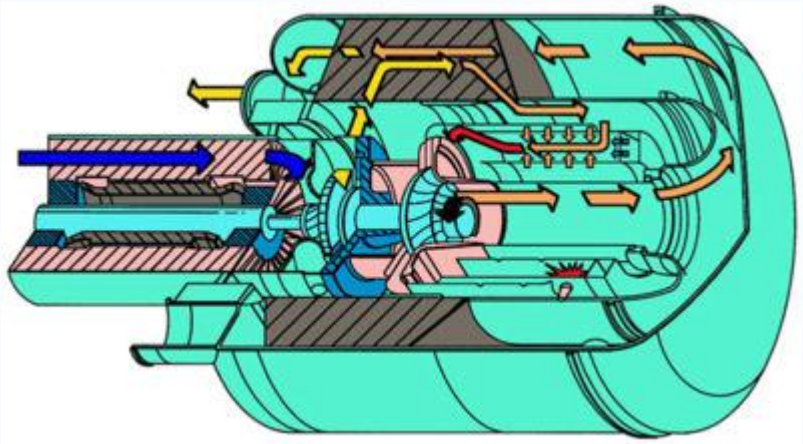
Modern turbine design carries the calculations further. Computational fluid dynamics dispenses with many of the simplifying assumptions used to derive classical formulas and computer software facilitates optimization. These tools have led to steady improvements in turbine design over the last forty years.

The primary numerical classification of a turbine is its ***specific speed***. This number describes the speed of the turbine at its maximum efficiency with respect to the power and flow rate. The specific speed is derived to be independent of turbine size. Given the fluid flow conditions and the desired shaft output speed, the specific speed can be calculated and an appropriate turbine design selected.

The specific speed, along with some fundamental formulas can be used to reliably scale an existing design of known performance to a new size with corresponding performance.

Off-design performance is normally displayed as a turbine map or characteristic.

2.5.3 Gas turbine



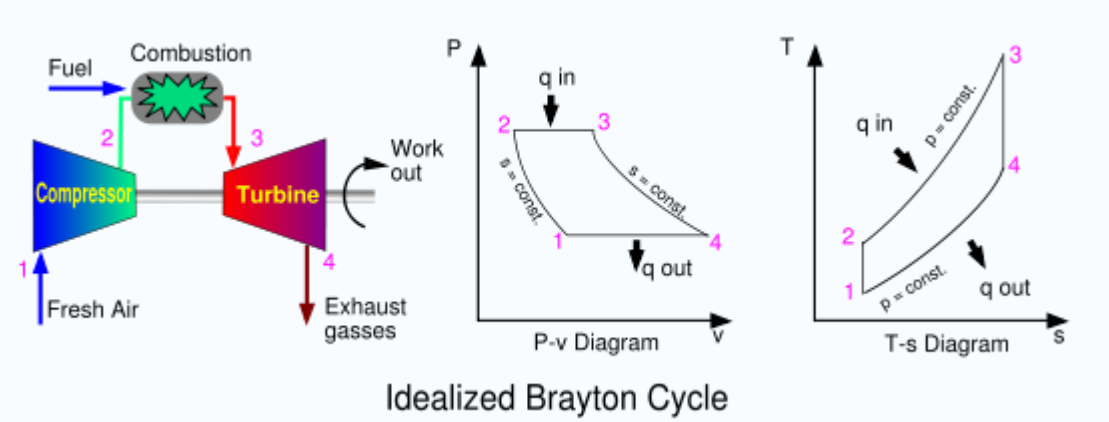
A **gas turbine**, also called a **combustion turbine**, is a rotary engine that extracts energy from a flow of hot gas produced by combustion of gas or fuel oil in a stream of compressed air. It has an upstream air compressor (radial or axial flow) mechanically coupled to a downstream turbine and a combustion chamber in between. **Gas turbine** may also refer to just the turbine element.

Energy is released when compressed air is mixed with fuel and ignited in the combustor. The resulting gases are directed over the turbine's blades, spinning the turbine, and, mechanically, powering the compressor. Finally, the gases are passed through a nozzle, generating additional thrust by accelerating the hot exhaust gases by expansion back to atmospheric pressure.

Energy is extracted in the form of shaft power, compressed air and thrust, in any combination, and used to power electrical generators.

Theory of operation

Gas turbines are described thermodynamically by the Brayton cycle, in which air is compressed isentropically, combustion occurs at constant pressure, and expansion over the turbine occurs isentropically back to the starting pressure.

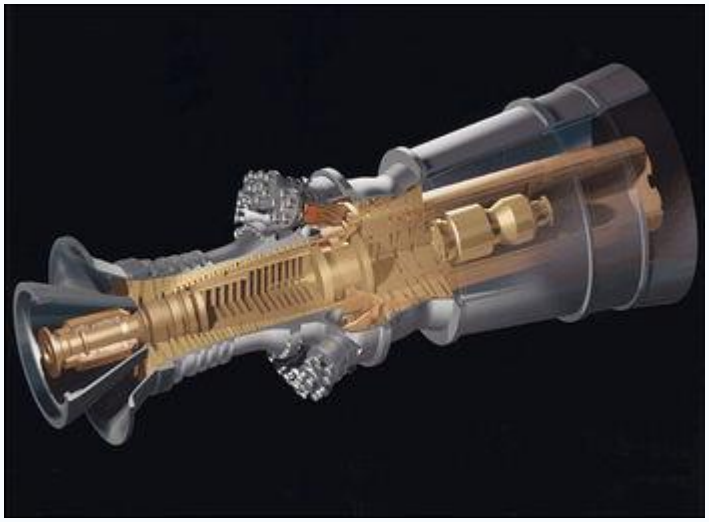


Idealized Brayton Cycle

As with all cyclic heat engines, higher combustion temperature means greater efficiency. The limiting factor is the ability of the steel, nickel, ceramic, or other materials that make up the engine to withstand heat and pressure. Considerable engineering goes into keeping the turbine parts cool. Most turbines also try to recover exhaust heat, which otherwise is wasted energy. Recuperators are heat exchangers that pass exhaust heat to the compressed air, prior to combustion. Combined cycle designs pass waste heat to steam turbine systems. And combined heat and power (co-generation) uses waste heat for hot water production.

.

Gas turbines for electrical power production



GE H series power generation gas turbine. This 480-megawatt unit has a rated thermal efficiency of 60% in combined cycle configurations.

Simple cycle gas turbines in the power industry require smaller capital investment than either coal or nuclear power plants and can be scaled to generate small or large amounts of power. Also, the actual construction process can take as little as several weeks to a few months, compared to years for base load power plants. Their other main advantage is the ability to be turned on and off within minutes,

supplying power during peak demand. Since they are less efficient than combined cycle plants, they are usually used as peaking power plants, which operate anywhere from several hours per day to a couple dozen hours per year, depending on the electricity demand and the generating capacity of the region. In areas with a shortage of base load and load following power plant capacity, a gas turbine power plant may regularly operate during most hours of the day and even into the evening. A typical large simple cycle gas turbine may produce 100 to 300 megawatts of power and have 35 to 40% thermal efficiency. The most efficient turbines have reached 46% efficiency.

Combined-Cycle Gas Turbines

With the increasing availability of natural gas (methane) and its competitive price, prime movers based on the gas turbine are being increasingly used. Because of the high temperatures obtained by gas combustion, the efficiency of a gas turbine is comparable to that of a steam turbine, with the additional advantage that there is still sufficient heat in the gas-turbine exhaust to raise steam in a conventional boiler to drive a steam turbine coupled to another electricity generator. This is known as a combined-cycle gas-turbine (CCGT) plant, a schematic layout of which is shown in Figure 2.7. Combined efficiencies now being achieved are between 56 and 58 per cent.The advantages of CCGT plant are the fast start up and shut down (2—3 mm for the gas turbine, 20 mm for the steam turbine), the flexibility possible for load following, the comparative speed of installation because of its modular nature and factory-supplied units, and its ability to run on oil (from local storage tanks) if the gas supply is interrupted. Modern installations are fully automated and require only a few operatives to maintain 24 h running or to supply peak load, if needed.

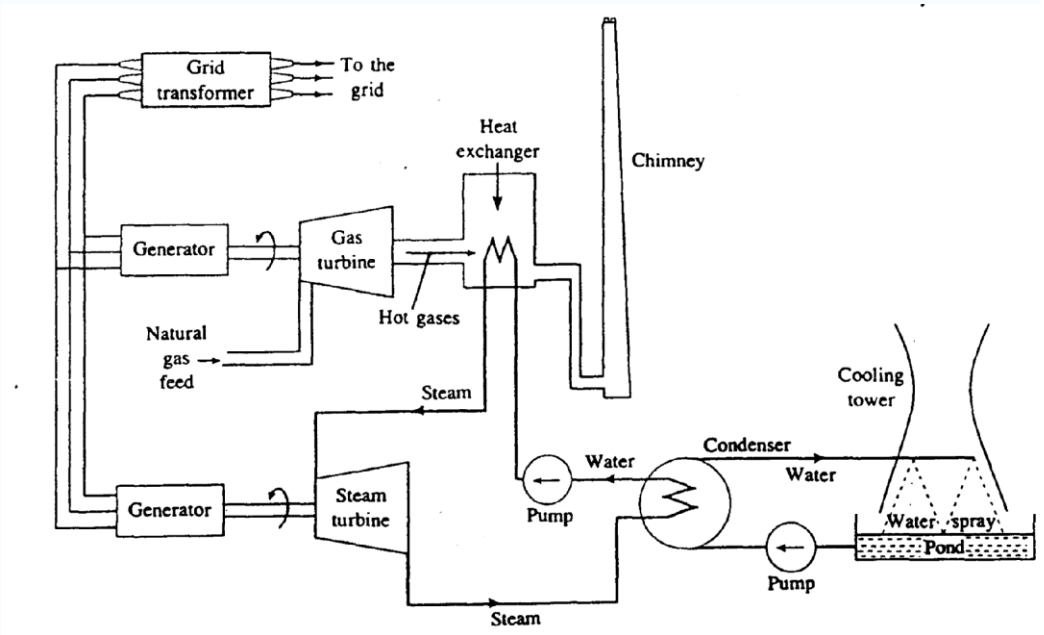


Figure 2.7 Schematic diagram of a combined-cycle gas-turbine power station

Advantages and disadvantages of gas turbine engines

Advantages of gas turbine engines

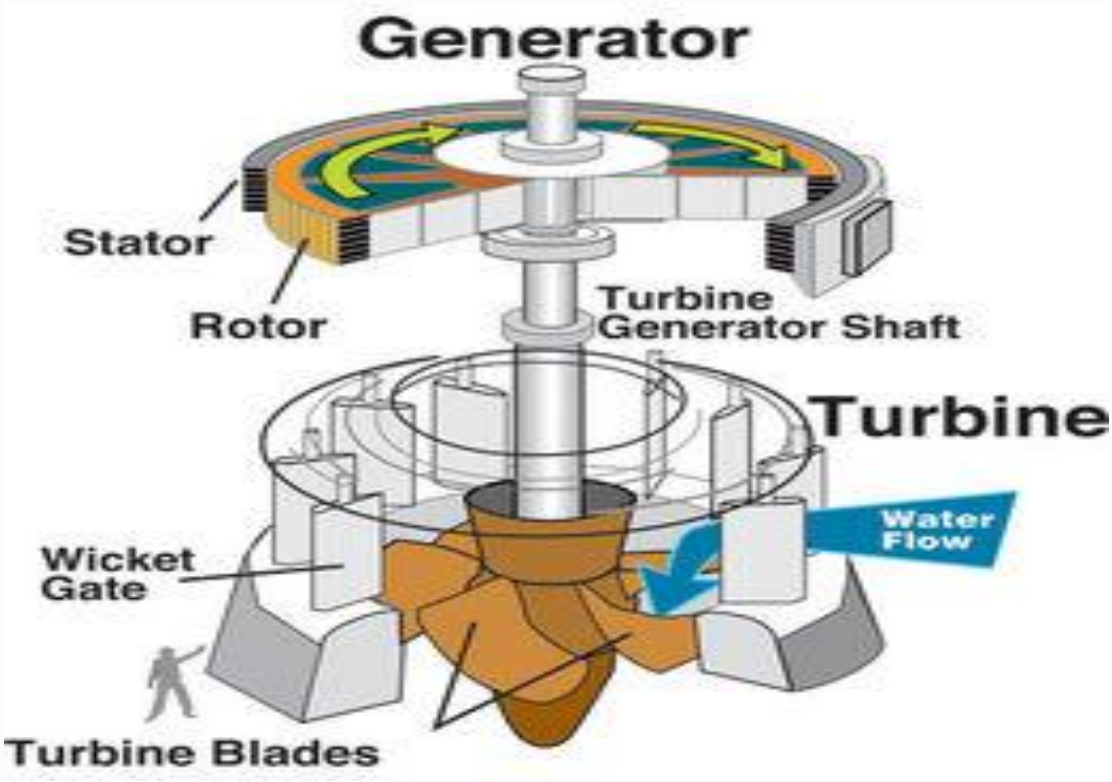
- Very high power-to-weight ratio, compared to reciprocating engines (ie. most road vehicle engines);
- Smaller than most reciprocating engines;
- Moves in one direction only, and doesn't vibrate, so very reliable;
- Simpler design.

Disadvantages of gas turbine engines

- Cost is much greater than for a similar-sized reciprocating engine (very high-performance, strong, heat-resistant materials needed);
- Use more fuel when idling compared to reciprocating engines - not so good unless in continual operation.

These disadvantages explain why road vehicles, which are smaller, cheaper and follow a less regular pattern of use than tanks, helicopters, large boats and so on, do not use gas turbine engines, regardless of the size and power advantages imminently available.

2.5.4 Water turbine



Kaplan turbine and electrical generator cut-away view.

A **water turbine** is a rotary engine that takes energy from moving water.

Water turbines were developed in the nineteenth century and were widely used for industrial power prior to electrical grids. Now they are mostly used for electric power generation. They harness a clean and renewable energy source.

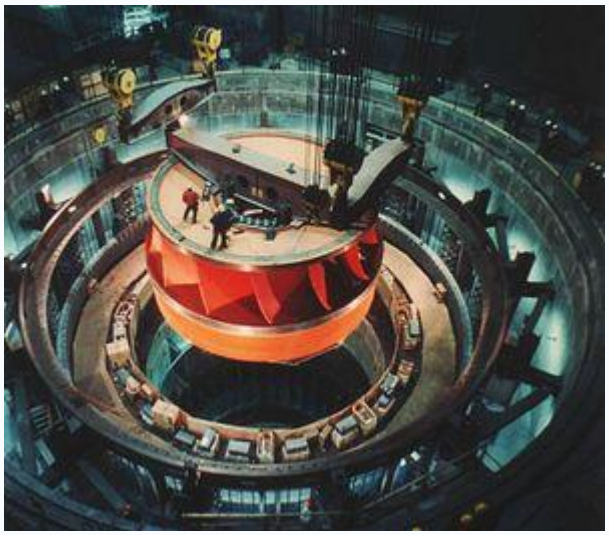
Swirl

Water wheels have been used for thousands of years for industrial power. Their main shortcoming is size, which limits the flow rate and head that can be harnessed.

The migration from water wheels to modern turbines took about one hundred years. Development occurred during the **Industrial revolution**, using scientific principles and methods. They also made extensive use of new materials and manufacturing methods developed at the time.

The main difference between early water turbines and water wheels is a swirl component of the water which passes energy to a spinning rotor. This additional component of motion allowed the turbine to be smaller than a water wheel of the same power. They could process more water by spinning faster and could harness much greater heads. (Later, impulse turbines were developed which didn't use swirl).

Time line



A Francis turbine runner, rated at nearly one million hp (750 MW), being installed at the Grand Coulee Dam

A propeller-type runner rated 28,000 hp (21 MW)

Theory of operation

Flowing water is directed on to the blades of a turbine runner, creating a force on the

blades. Since the runner is spinning, the force acts through a distance (force acting through a distance is the definition of work). In this way, energy is transferred from the water flow to the turbine.

Types of water turbines

Before discussing the types of turbine used, a brief comment on the general modes of operation of hydroelectric stations will be given. The vertical difference between the upper reservoir and the level of the turbines is known as the head. The water falling through this head gains kinetic energy which it then imparts to the turbine blades. There are three main types of installation, as follows:

1. High head or stored—the storage area or reservoir normally fills in longer than 400 h;

2. Medium head or pondage—the storage fills in 200—400 h;

3. Run of river—the storage (if any) fills in less than 2 h and has 3—15 m head.

Associated with these various heights or heads of water level above the turbines are particular types of turbine. These are:

1. Pelton—This is used for heads of 1 84—i 840 m (600—6000 ft) and consists of a bucket wheel rotor with adjustable flow nozzles.

2. Francis—This is used for heads of 37—490 m (120—1600 ft) and is of the mixed flow type.

3. Kaplan—This is used for run-of-river and pondage stations with heads of up to 61 m (200ft). This type has an axial-flow rotor with variable-pitch blades.

Pumped storage

Some water turbines are designed for Pumped storage hydroelectricity. They can reverse flow and operate as a pump to fill a high reservoir during off-peak electrical hours, and then revert to a turbine for power generation during peak electrical demand. This type of turbine is usually a Francis in design.

Efficiency

Large modern water turbines operate at mechanical efficiencies greater than 90% (not to be confused with thermodynamic efficiency). Typical efficiency curves for each type of turbine are shown in Figure 2.8. As the efficiency depends upon the head of water, which is continually fluctuating, often water consumption in cubic meters per kilowatt-hour is used and is related to the head of water. Hydroelectric plant has the ability to start up quickly and the advantage that no losses are incurred when at a standstill. It has great advantages, therefore, for power generation to meet peak loads at minimum cost, working in conjunction with thermal stations. By using remote control of the hydro sets, the time from the instruction to start up to the actual connection to the power network can be as short as 3 min.

At certain periods when water availability is low or when generation is not required from hydro sets, it may be advantageous to run the electric machines as motors supplied from the power system. This then act as synchronous compensator To reduce the amount of power required, the water is pushed below the turbine runner by compressed air. This is achieved by closing the water inlet valve and injecting compressed air which pushes the water towards the lower reservoir. The runner now rotates in air and thus requires much less motive power than in water.

.

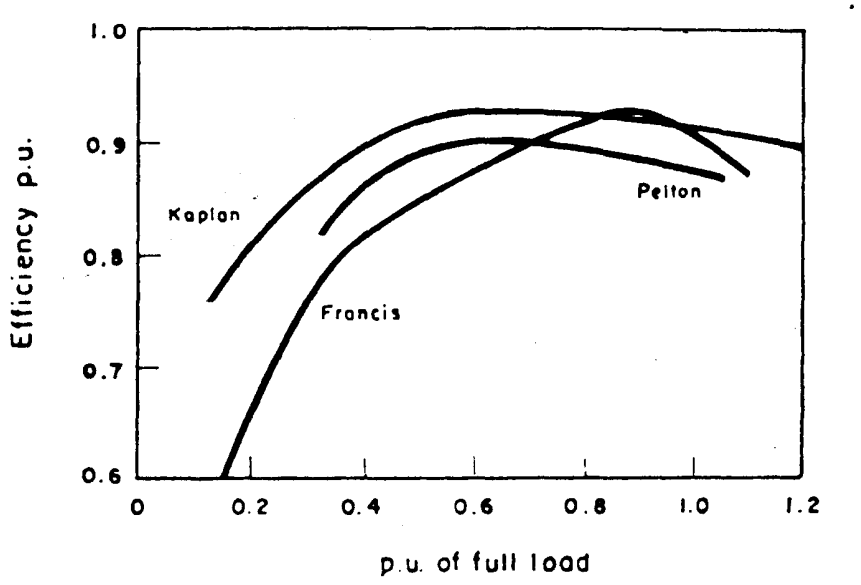


Fig.2.8 Typical efficiency curves of hydraulic turbines

Power of water turbine

The power available in a stream of water is;

$$P = \eta \cdot \rho \cdot g \cdot h \cdot \dot{v}$$

where:

- P = power (J/s or watts)
- η = turbine efficiency
- ρ = density of water (1000 kg/m^3)
- g = acceleration of gravity (9.81 m/s^2)
- h = head (m). For still water, this is the difference in height between the inlet and outlet surfaces. Moving water has an additional component added to account for the kinetic energy of the flow. The total head equals the *pressure head* plus *velocity head*.
- $\dot{v}$ = flow rate (m^3/s) through the turbine

Example1: Determine the firm capacity and the yearly gross output at a site of hydroelectric plant where it has bean estimated that the minimum flow rate of approximately 94m3/sec will be available at a hydraulic project with a head of 50 meters.

Solution :

Minimum flow rate available , $\dot{v}$ = 94 m3/sec = 94000 kg/sec (1m3 of water weighs 1000 kg).

Head of water = 50 m = h

Work done per second = $\dot{v}$ x h = 94000 x 50 kg.m/sec

= 94000 x 50 x 9.81 Nm/sec

Gross plant capacity = 94000 x 50 x 9.81/ 1000 kW

Firm capacity of the plant = Efficiency of the plant x Gross plant capacity

= (94000 x 50 x 9.81/ 1000) x 0.8

= 36885 kW

Yearly gross output =plant firm capacity x 24x 365=323x10^6 kWh.

Specific speed

The specific speed, n_s , of a turbine characterizes the turbine's shape in a way that is not related to its size. This allows a new turbine design to be scaled from an existing design of known performance. The specific speed is also the main criteria for matching a specific hydro site with the correct turbine type.

The specific speed of a turbine can also be defined as the speed of an ideal, geometrically similar turbine, which yields one unit of power for one unit of head.

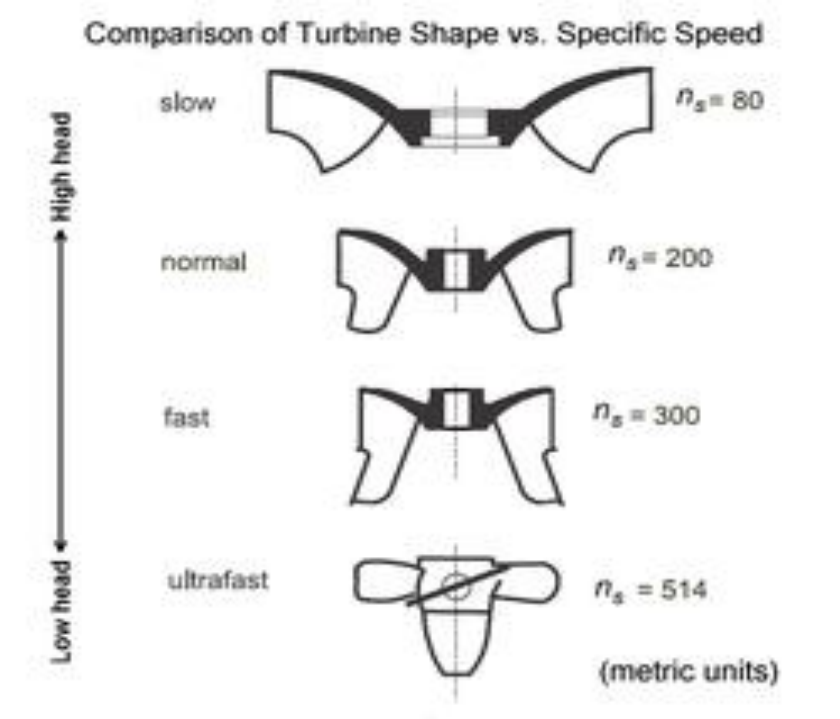
The specific speed of a turbine is given by the manufacturer (along with other ratings) and will always refer to the point of maximum efficiency. This allows accurate calculations to be made of the turbine's performance for a range of heads and flows.

$$n_s = n\sqrt{P}/H^{5/4}$$ dimensioned parameter

n = rpm

$$N_s = \frac{\Omega\sqrt{P/\rho}}{gH^{5/4}}$$ (dimensionless parameter)

Ω = angular velocity (radians/second)



Nuclear Energy for Power Generation

Nuclear power

There is strategic as well as economic necessity for nuclear power in the most of the world. The strategic importance lies primarily in the fact that one large nuclear power plant saves more than 50,000 barrels of oil per day. At $90 per barrel (2007) such a power plant would pay for its capital cost in a short years.
For those countries that now rely on but do not have oil, or must reduce the importation of foreign oil, these strategic and economic advantages are obvious,
For those countries that are oil exporters, nuclear power represents an insurance again the day when oil is depleted. A modest start now will assure that they would not left behind when the time comes to have to use nuclear technology.
The unit costs per kilowatthour for nuclear energy are now comparable to or lows than the unit costs for coal in most parts of the world. Other advantages are the lack of environmental problems that are associated with coal- or oil-fired power plants the near absence of issues of mine safety, labor problems, and transportation ,bottle necks. Natural gas is a good, relatively clean-burning fuel, but it has some availability problems in many countries and should, in any case, be conserved for small-scale industrial and domestic uses. Thus nuclear power is bound to become the social choice relative to other societal risks and overall health and safety risks.

Yet the nuclear industry is facing many difficulties, primarily as a result of the negative impact of the issues of nuclear safety, waste disposal, weapons proliferation, and economics on the public and government. The impact on the public is complicated by delays in licensing proceedings, court, and ballot box challenges. These posed severe obstacles to electric utilities planning nuclear power plants, the result being scheduling problems, escalating and unpredictable costs, and economic risks even before a construction permit is issued.
We shall begin in this chapter by covering the energy-generation processes in nuclear reactors by starting with the structure of the atom and its nucleus and the reactions that give rise to such energy generation. These include fission, fusion, and different types of neutron-nucleus interactions and radioactivity.

Basic Review of Nuclear Physics

In 1803 John Dalton, attempting to explain the laws of chemical combination, proposed his simple but incomplete atomic hypothesis. He postulated that all elements consisted of indivisible minute particles of matter, atoms, that were different for different elements and preserved their indentity in chemical reactions. In 1811 Amadeo Avogadro introduced the molecular theory based on the molecule, a particle of matter composed of a finite number of atoms. It is now known that the atoms are themselves composed of subparticles, common among atoms of all elements.

Atom. An atom consists of positively charged nucleus having neutrons and protons, and number of much lighter negatively charged electrons orbiting the nucleus. Protons are positively charged and its magnitude is equal to the magnitude of charge that is negative on an electron. The charge on each proton is 1.602×10^{-19} coulomb. Thus an atom is electrically uncharged as the number of protons is equal to the number of electrons.

The number of protons in a nucleus is called the **atomic number**, which is normally represented as Z. The total number of protons and neutrons in the nucleus is called **mass number** and is normally denoted by A. Therefore, the number of neutrons in the atom will be (A — Z). The nuclear symbol is written as

$$_{Z}X^{A}$$

where X is chemical symbol. The chemical nature of an element is determined by its atomic number. Hydrogen ($_1H^1$) has one nucleus composed of 1 proton, no neutron and 1electron.Most of the weight of an atom is concentrated in the nucleus. The radius of a nucleus is of the order of 10^{-16} m and that of atom is 10^{-11} m .

Figure 2-11 shows three atoms. Hydrogen has a nucleus composed of one proton, no neutrons, and one orbital electron. It is the only atom that has no neutrons. Deuterinm has one proton and one neutron in its nucleus and one orbital electron. Helium contains two protons, two neutrons, and two electrons. The electrons exist in orbits, and each is quantitized as a lumped unit charge as shown

Most of the mass of the atom is in the nucleus. The weight of a proton, electron and of neutron are represented in terms of the atomic mass unit **(amu)**, which is (1/16)th the weight of the oxygen atom. One atomic mass unit is equal to 1.66×10^{-27} kg.

Proton mass (m_p,) = 1.007277 amu = 1.673×10^{-27} kg

Neutron mass (m_n) = 1.008665 amu = 1.674×10^{-27} kg

Electron mass (m_e) = 0.0005486 amu = 9.107×10^{-31} kg

The atoms having the same number of protons (or electrons) have similar chemical properties. They differ mainly in their masses. Such atoms are called isotopes. Some of the isotopes of some elements are unstable and disintegrate spontaneously. Many isotopes do not appear in nature and are synthesized in the laboratory or in nuclear reactors. Two other particles are of importance, namely, the positron and neutrino. The positron is a positively charged electron having the symbols $_{+1}e^0$, e^+ or β^+ whereas the symbol for electron is $_{-1}e^0$, e^- or β^- . The neutrino is a tiny, electrically neutral particle, ejected along with β particle during the nuclear fission.

Electrons that orbit in the outermost shell of an atom are called valence electrons. The outermost shell is called the valence shell. Thus, hydrogen has one valence electron and its K shell is the valence shell, etc. Chemical properties of an element are a function of the number of valence electrons. The electrons play little or not part in nuclear interactions.

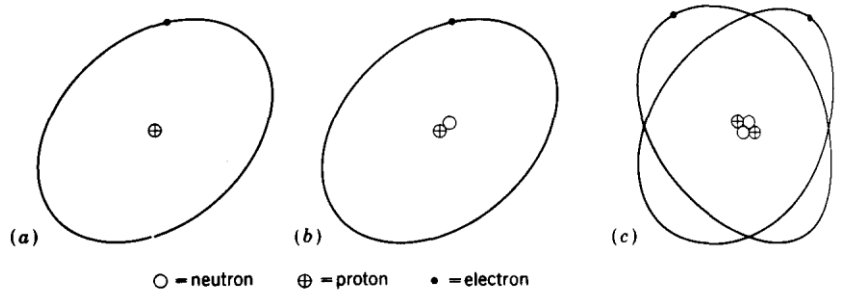


Figure 2-11 Structure of some light atoms: (a) hydrogen; (b) deuterium or heavy hydrogen, and (c) helium.

Many elements (such as hydrogen, above) appear in nature as mixtures of isotopes of varying abundances. For example, naturally occurring uranium, called natural uranium, is composed of 99.282 mass percent U^{238}, 0.712 mass percent U^{235} and 0.006 mass percent U^{234} where the atomic number is deleted. It is 92 in all cases. Many isotopes that do not appear in nature are synthesized in the laboratory or in nuclear reactors. For example, uranium is known to have a total of 14 isotopes that range in mass numbers from 227 to 240.
Figure 2-12 shows, schematically, the structure of H^1, He^4 and some heavier atoms and the distribution of their electrons in various orbits.

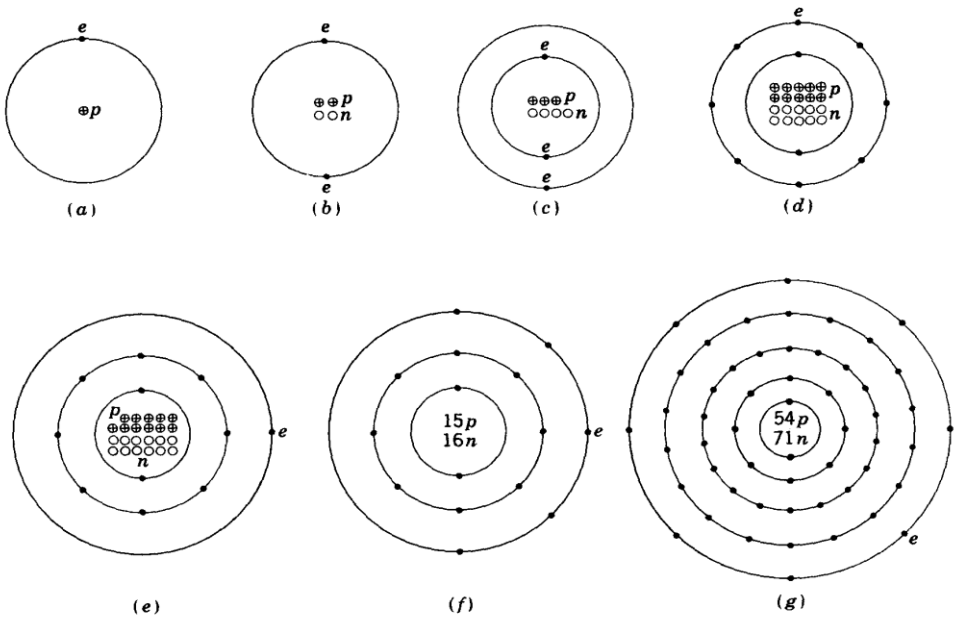


Fig.2-12. Structure of some atoms (a) hydrogen(Z=1,A=1),(b)helium(Z=2,A=4), (c) lithium(Z=3,A=7),(d) neon(Z=10,A=20) , (e) sodium(Z=11,A=23) , (f) phosphorous(Z=15,A=31),and xenon (Z=54,A=125).

ENERGY FROM NUCLEAR REACTIONS

The energy corresponding to the change in mass in a nuclear reaction is calculated from Einstein's law, Eq. (2-1), here repeated

$$\Delta E = \frac{1}{g_c} \Delta m c^2 \qquad (2\text{-}1)$$

where g is a conversion factor that has the following values

1.0	$kg \cdot m/(N \cdot s^2)$
1.0	$g \cdot cm^2/(erg \cdot s^2)$
32.2	$lb_m \cdot ft/(lb_f \cdot s^2)$
4.17×10^8	$lb_m \cdot ft/(lb_f \cdot hr^2)$
0.965×10^{18}	$amu \cdot cm^2/(MeV \cdot s^2)$

Thus if Δ m is in kilograms and c in meters per second, ΔE will be in joules. Since $c = 3 \times 10^8$ m/s, Eq. (2-1) can be written in the form

$$\Delta E \text{ (in J)} = 9 \times 10^{16} \Delta m \text{ (in kg)}$$

But as it is convenient to express the masses of nuclei in amu = 1.66×10^{-27} kg and the energy in joules (J) and MeV, Eq. (2-1) becomes

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ Joule}$$

$$1 \text{ MeV} = 10^6 \times 1.602 \times 10^{-19} = 1.602 \times 10^{-13} \text{ J}$$

$$\Delta E = 1.66 \times 10^{-27} \times (3 \times 10^8)^2 = 1.494 \times 10^{-10} \text{ J}$$

$$\Delta E \text{ (in J)} = 1.49 \times 10^{-10} \Delta m \text{ (in amu)}$$

$$\Delta E \text{ (in MeV)} = 931 \Delta m \text{ (in amu)}$$

a useful relationship to remember.

NUCLEAR FUSION AND FISSION

Nuclear reactions of importance in energy production are fusion, fission, and radio activity. Radioactivity will be discussed in the next section. Infusion, two or more light nuclei fuse to form a heavier nucleus. In fission, a heavy nucleus is split into two or more lighter nuclei. In both, there is a decrease in mass resulting in exothermic energy.

Fusion

Energy is produced in the sun and stars by continuous fusion reactions in which four nuclei of hydrogen fuse in a series of reactions involving other particles that continually appear and disappear in the course of the reactions, such as He nitrogen, carbon, and other nuclei, but culminating in one nucleus of helium and two positrons

$$4\,{}_1H^1 \rightarrow {}_2He^4 + 2\,{}_{+1}e^0$$

resulting in a decrease in mass of about 0.0276 amu, corresponding to 25.7 MeV. The heat produced in these reactions maintains temperatures of the order of several million degrees in their cores and serves to trigger and sustain succeeding reactions.
Fusion reactions are called thermonuclear because very high temperatures are required to trigger and sustain them. It is considered as very complicated process, therefore fusion power plants will not be covered in this text.

Fission

Unlike fusion, which involves nuclei of similar electric charge and therefore requires high kinetic energies, fission can be caused by the neutron, which, being electrically neutral, can strike and fission the positively charged nucleus at high, moderate, or low speeds without being repulsed. Fission can be caused by other particles, but neutrons are the only practical ones that result in a sustained reaction because two or three neutrons are usually released for each one absorbed in fission. These keep the reaction going. There are only a few fissionable isotopes. U^{235}, Pu^{239} and U^{233}, are fissionable by neutrons of all energies. U^{238}, Th^{223} and Pu^{240} are fissionable by high-energy neutrons only. An example, shown schematically in Fig. 2.13, is

$$_{92}U^{235} + {}_0n^1 \rightarrow {}_{54}Xe^{140} + {}_{38}Sr^{94} + 2{}_0n^1 \qquad (2.2)$$

The immediate (prompt) products of a fission reaction, such as Xe^{140} and Sr^{94} above, are called fission fragments. They, and their decay products , are called fission products.

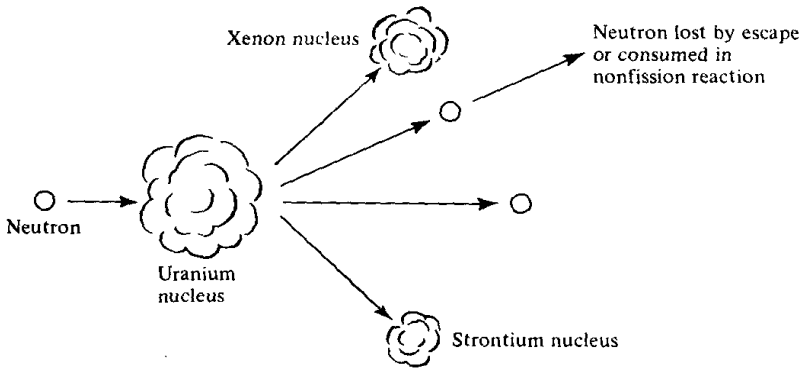


Figure 2-13 A typical fission reaction

ENERGY FROM FISSION AND FUEL BURNUP

There are many fission reactions that release different energy values. The one in Eq. (2-2), for example, yields 196 MeV. Another

$$_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{56}Ba^{137} + {}_{36}Kr^{97} + 2{}_{0}n^{1}$$

has the mass balance

$$235.0439 + 1.00867 \rightarrow 136.9061 + 96.9212 + 2 \times 1.00867$$

$$236.0526 \rightarrow 235.8446$$

$$\Delta m = 235.8446 - 236.0526 = -0.2080 \text{ amu}$$

Thus

$$\Delta E = 931 \times -0.2080 = -193.6 \text{ MeV} = -3.1 \times 10^{-11} \text{ J}$$

$$= -2.937 \times 10^{-11} \text{ Btu}$$

However, exothermic reaction release energy with mass reaction, while endothermic Reaction absorbs energy with mass increase.

On the average the fission of a U^{235} nucleus yields about 190 MeV. The same figure roughly applies to U^{233} and $Pu^{239.}$ This amount of energy is prompt, i.e., released at the time of fission. However, the total energy produced is slightly greater (=200MeV) Therefore the complete fission of U^{235} produces:
Energy produces by = (Avogadro's number (constant)/ U^{235} atomic mass) x 200
Fission of 1 g of U^{235}

$= (6.02 \times 10^{23} \times 200) / 235.043$
$= 0.513 \times 10^{24}$ MeV
$= 8.19 \times 10^{10}$ J
$= 22.6 \times 10^{3}$ kWh
= 22.6 MWh
= (22.6/24)=0.948 MW-day
$\cong$ 1 MW-day

Hence 1g of fissionable material generates nearly 1 MW-day of energy. This relates to fuel burn up. Thus one ton of U^{235} generates:

1000x1000 x1= 1000,000 MW-day

Example 1. Assuming 80% of neutrons are absorbed by U-235 cause fission and rest

being absorbed by the non-fission capture to produce an isotope U-236, estimate the fuel consumption of U-235 per hour to produce 100 MW of power. Each fission of U-235 yields 190 MeV of useful energy.

Solution : since

$$\text{190-MeV energy in terms of Joule} = 190 \times 10^6 \times 1.60 \times 10^{-19}$$
$$= 3.04 \times 10^{-11} \text{ J}$$

Number of fission required to produce one joule of energy is

$$\frac{1}{3.04 \times 10^{-11}} = 3.29 \times 10^{10}$$

The number of nuclei burnt during 1 hour per MW of power is

$$\frac{10^6 \times 3.29 \times 10^{10} \times 3600}{0.80} = 1.48026 \times 10^{20} \text{ absorption/hr}$$

Mass of U-235 consumed to produce 1-MW power is

$$\frac{1.48026 \times 10^{20} \times 235}{\text{Avogadro's constant } (=6.023 \times 10^{23})} = 0.0577555 \text{ g/hr}$$

Therefore, fuel consumption of U-235 to produce 100 MW will be 5.7756 g/hr.

Radioactivity. Most of the isotopes starting with $Z \geq 81$ are not stable due to small binding energy per nucleon and emit radiation till a more stable nucleus is reached. Thus, a spontaneous disintegration process is called radioactive decay, which is accompanied by the radioactive rays (α ,β and γ). The resulting nucleus is called the daughter and the original nucleus is called the parent. The radioactivity is always accompanied by a decrease of mass or liberation of energy. Radioactive isotopes, both natural and man-made, emit (a) α particles, (b) β particles, (c) γ radiation, (d) neutrons and (e) neutrinos. They also undergo positron decay and orbital electron .absorption, called K-capture.

Radiation or nuclear disintegration occurs at a definite rate, which is often expressed in the form of half-life that is the time in which half of an original atom disintegrates.the rate of decay is also called activity. The half- life is defined as

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.6931}{\lambda}$$

where λ is decay constant. If N_o is the number of nuclei of one specimen, half of the N_o decay after one half-life; one-half of the remaining atom or 1/4 of N_o decays during the second half-life and so on.

The rate of release of radiation by a radioisotope is dependent on the activity, a, which

is the number of disintegrations per second. Since the decay constant λ is the change of decay each second, then with N nuclei present, the activity is

$$a = \lambda N$$

$$N = \frac{\text{Avogadro's constant } (= 6.023 \times 10^{23})}{\text{Atomic mass}}$$

The useful unit of activity is the curie (Ci). One curie is equivalent of 3.7×10^{10} disintegration/second.

Example2 : Find the binding energy in MeV of ordinary helium $_2He^4$ for which

atomic mass is 4.002603 amu. Given that $m_p = 1.007277$ amu, $m_n = 1.008665$ amu and $m_e = 0.00055$ amu.

Solution : Molecule of helium has 2 protons, 2 electrons and 2 neutrons .Therfore

$$\text{Half-life} = \frac{0.6931}{\lambda} = \frac{0.6931}{1.3566 \times 10^{-11}} = 5.10909 \times 10^{10} \text{ sec}$$

Therefore,

$$\text{Half-life} = \frac{5.10909 \times 10^{10}}{365 \times 24 \times 60 \times 60} = 1620.08 \text{ yr}$$

(b) Number of atoms per gram of radium-226 is

$$\frac{\text{Avogadro's constant}}{\text{Atomic mass}} = \frac{6.023 \times 10^{23}}{226.095} = 2.6639 \times 10^{21}$$

and

$$\begin{aligned} \text{Activity } a &= \lambda N = 1.3566 \times 10^{-11} \times 2.6639 \times 10^{21} \\ &= 3.614 \times 10^{10} \text{ disintegration/second} \\ &= 0.977 \text{ Ci} \end{aligned}$$

TYPES OF REACTORS

A nuclear reactor can be classified in different ways such as on the basis of types of core used, moderator used, coolant used, fuel used and neutron energy. The main types of the commercial fission reactors in the world used for electrical power production are:

A. Thermal reactors

1. Pressurized Water Reactor (PWR)
2. Boiling Water Reactor (BWR)
3. Heavy Water Cooled and Moderated (CANDU Type) Reactor
4. Gas-Cooled Reactor

B. Fast reactor

5. Fast Breeder Reactor (FBR)

MAIN COMPONENTS OF REACTORS

The basic reactor consists of the fuel in the form of rods or pellets situated in an environment (moderator) which will slow down the neutrons and fission products and in which the heat is evolved. The moderator can be light or heavy water or graphite. Also situated in the moderator are movable rods which absorb neutrons and hence exert control over the fission process. In some reactors the cooling fluid is pumped through channels to absorb the heat, which is then transferred to a secondary loop in which steam is produced for the turbine, which in turn drives electric generators.

Fuel rods. A fuel rod is a zircaloy tube, filled with pellets of uranium oxide (UO_2). These fuel assemblies can be lifted into and out of the reactor mechanically, allowing fuel replenishment while the reactor is in operation. The rods are arranged into fuel assemblies in the reactor core. Figure 2.14 shows a schematic diagram for a fuel rod.

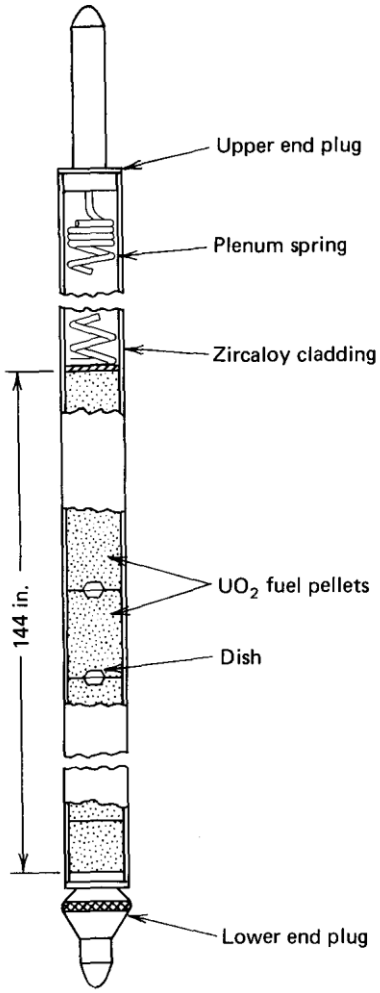


Fig.2-14 Typical fuel rod.

Each fuel assembly contains 49 fuel rods. Each fuel rod contains uranium dioxide pellets approximately 0.5 inches in diameter. The pellets are enclosed in zircaloy-2 tubes. In addition to fuel pellets, there is a plenum filled with helium and provided with a mechanical spring on top of the fuel rod. This arrangement is designed to accommodate axial expansion. The zircaloy-2 tube is sealed by welding plugs in both ends. This cladding has a thickness of 0.032 in.

Moderator. This is material which slows down the neutrons released from fission so that they cause more fission. It is usually water, but may be heavy water or graphite.

Shielding. Shielding is used to give the protection against the radiations during the process of fission in reactor.

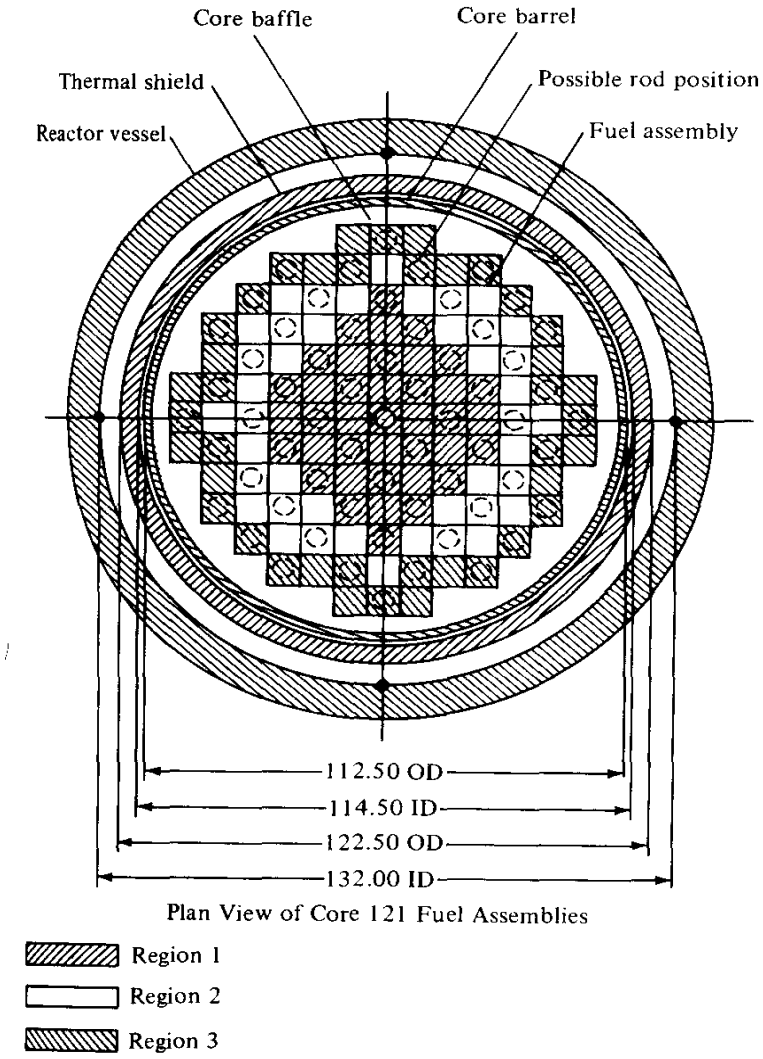


Fig.2-15

The core is surrounded by a form-fitting baffle (Fig.2.15) that restricts the bulk of upward coolant flow to the fuel. The baffle is in turn surrounded by the core barrel. A small amount of coolant is allowed to flow between baffle and barrel. The coolant is diffused uniformly into the core by a perforated flow-mixture plate situated between the core support plate and the lower core plate. A thermal shield, supported by the core barrel, is provided to intercept core radiations and protect the pressure vessel.

The primary coolant enters the reactor vessel at about 552°F (289°C) via a number of inlet nozzles (two for 500 MW, four for 1000 MW and larger, three for intermediate) and flows downward through the annulus between the core barrel and reactor vessel wall (Fig.2.15), thus cooling the thermal shield on both sides. It then enters a plenum at the bottom of the vessel, reverses direction, goes upward through the core where it picks up fission heat, and leaves through an equal number of exit nozzles at about 605°F (3 18°C). The maximum coolant temperature at the exit of the center fuel assemblies is about 650°F (343°C). The reactor coolant pressure is 2235 psig (155 bar), greater than the saturation pressure at 650°F.

Control rods. These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it. (Secondary shutdown systems involve adding other neutron absorbers, usually in the primary cooling system.).

Coolant. A liquid or gas circulating through the core so as to transfer the heat from it. In light water reactors the moderator functions also as coolant.

Pressure vessel or pressure tubes. Usually a robust steel vessel containing the reactor core and moderator/coolant, but it may be a series of tubes holding the fuel and conveying the coolant through the moderator.

Steam generator. Part of the cooling system where the heat from the reactor is used to make steam for the turbine.

Containment. The structure around the reactor core which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any major malfunction inside. It is typically a meter-thick concrete and steel structure.

Most reactors need to be shut down for refueling, so that the pressure vessel can be opened up. In this case refueling is at intervals of 1-2 years, when a quarter to a third of the fuel assemblies are replaced with fresh ones. The CANDU and RBMK types have pressure tubes (rather than a pressure vessel enclosing the reactor core) and can be refueled while still generating electricity by disconnecting individual pressure tubes.

If graphite or heavy water is used as moderator, it is possible to run a power reactor on natural instead of enriched uranium. Natural uranium has the same elemental composition as when it was mined (0.7% U-235, over 99.2% U-238), enriched uranium has had the proportion of the fissile isotope (U-235) increased by a process called enrichment, commonly to 3.5 - 5.0%. In this case the moderator can be ordinary water, and such reactors are collectively called light water reactors. Because the light water absorbs neutrons as well as slowing them, it is less efficient as a moderator than heavy water or graphite.

Practically all fuel is ceramic uranium oxide (UO_2 with a melting point of 2800°C) and most is enriched. The fuel pellets (usually about 1 cm diameter and 1.5 cm long) are typically arranged in a long zirconium alloy (zircaloy) tube to form a fuel rod, the zirconium being hard, corrosion-resistant and permeable to neutrons. Up to 264 rods form a fuel assembly, which is an open lattice and can be lifted into and out of the reactor core. In the most common reactors these are about 3.5-4.0 meters.

Spent fuel assemblies are replaced one-third at a time, once a year, before they cause the reactor to lose energy. Fuel lasts for about three years until the build up of fission products starts slowing down the reaction.

Pressurized Water Reactor (PWR) and Boiling Water reactor:

In the U.S.A. and many other countries **pressurized-water** and **boiling-water** reactors are used. In general the PWR power plant is composed of two loops (see Fig.2-16):
- the coolant loop (the primary loop)
-the water steam loop (working – fluid loop) -
Water is pumped through the reactor and acts as a coolant and moderator, it enters the reactor vessel at about 289°C and flow downward between the core barrel and reactor vessel wall , thus cooling the thermal shield and goes downward and then upward through the core picking up fission heat and heated to 318°C.The water then transfer this heat to the working fluid in the steam generator (the steam pressure is greater than the vapor pressure at this temperature and the water leaves the reactor at below boiling point). The steam is then used in a Rankine-type cycle to generate electricity.

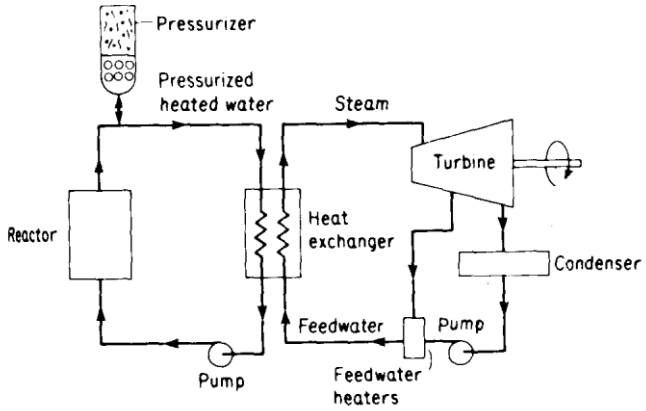
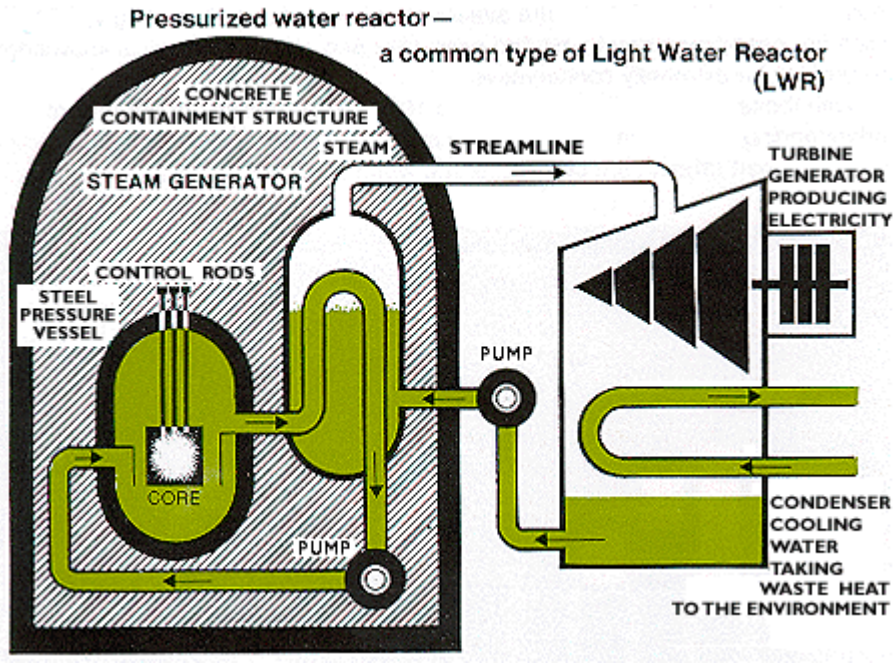


Figure2-16. Schematic arrangement of a PWR power plant.



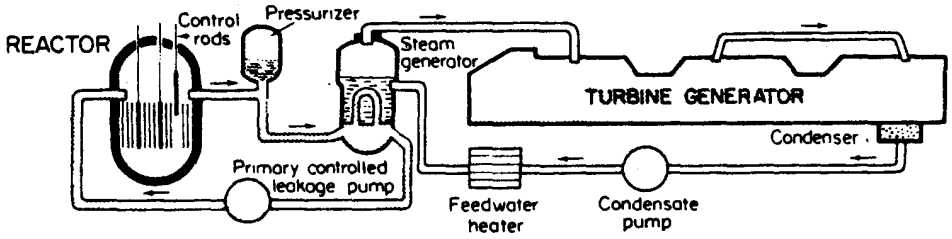


Fig. 2.17 Schematic diagram of a pressurized-water reactor (PWR)

Boiling water reactor

The boiling-water reactor was developed later than the pressurized-water type and - is now used extensively. Inside the reactor, heat is transferred to boiling water at a - pressure of 690 N/cm2. Schematic diagrams of these reactors are shown in Figures 2.17,2.18 and 2.19.

The nuclear steam supply system for a BWR plant mainly consists of reactor vessel and reactor coolant circuits. Figure shows a schematic diagram of a steam supply system. Unlike the PWR, this system does not have the intermediate heat exchanger, or steam generator, between the coolant loop and the feedwater and steam system. Steam is generated within the nuclear reactor and transferred directly to the steam turbine. In other words, water acts as a coolant as well as a working substance in power plant cycle. Therefore, the pressure in the BWR vessel is generally much lower than that in the PWR and, thus, a smaller vessel wall thickness is used in the BWR. A BWR produces saturated steam at about 545°F (285°C). The coolant thus serves the triple function of coolant, moderator, and working fluid. In its simplest form (Fig.2.18), a boiling-water-reactor power plant consists of a reactor, a turbine generator, a condenser and associated equipment (air ejector, cooling system, etc.), and a feed pump. Slightly subcooled liquid enters the reactor core at the bottom, where it receives sensible heat to saturation plus some latent heat of vaporization. When it reaches the top of the core, it has been converted into a very wet mixture of liquid and vapor. The vapor separates from the liquid, flows to the turbine, does work, is condensed by the condenser, and is then pumped back to the reactor by the feedwater pump.

The saturated liquid that separates from the vapor at the top of the reactor or in a steam separator flows downward via downcomers within or outside the reactor and mixes with the return condensate. This recirculating coolant flows either naturally, by the density differential between the liquid in the downcomer and the two-phase mixture in the core, or by recirculating pumps in the downcomer (not shown in the figure). This is similar to what happens in modern large fossil-fueled steam generators. Modern large boiling-water reactors are of the internal, forced recirculation type.

The saturated liquid that separates from the vapor at the top of the reactor or in a steam separator flows downward via downcomers within or outside the reactor and mixes with the return condensate. This recirculating coolant flows either naturally, by the density differential between the liquid in the downcomer and the two-phase

mixture in the core, or by recirculating pumps in the downcomer (not shown in the figure). This is similar to what happens in modern large fossil-fueled steam generators. Modern large boiling-water reactors are of the internal, forced recirculation type.

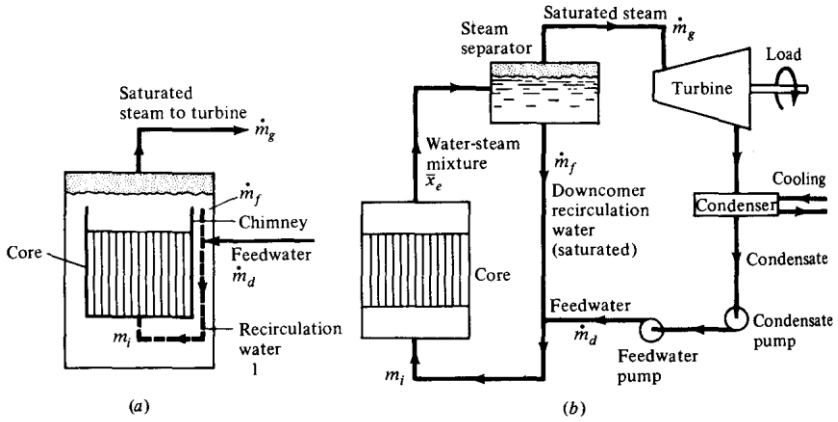


Figure2.18 Schematic of a BWR system: (a) internal and (b) external recirculation

Both pressurized- and boiling-water reactors use light water. The practical pressure limit for the pressurized-water reactor is about 167 bar (2500 p.s.i.), which limits its efficiency to about 30 per cent. However, the design is relatively straightforward and experience has shown this type of reactor to be stable and dependable.

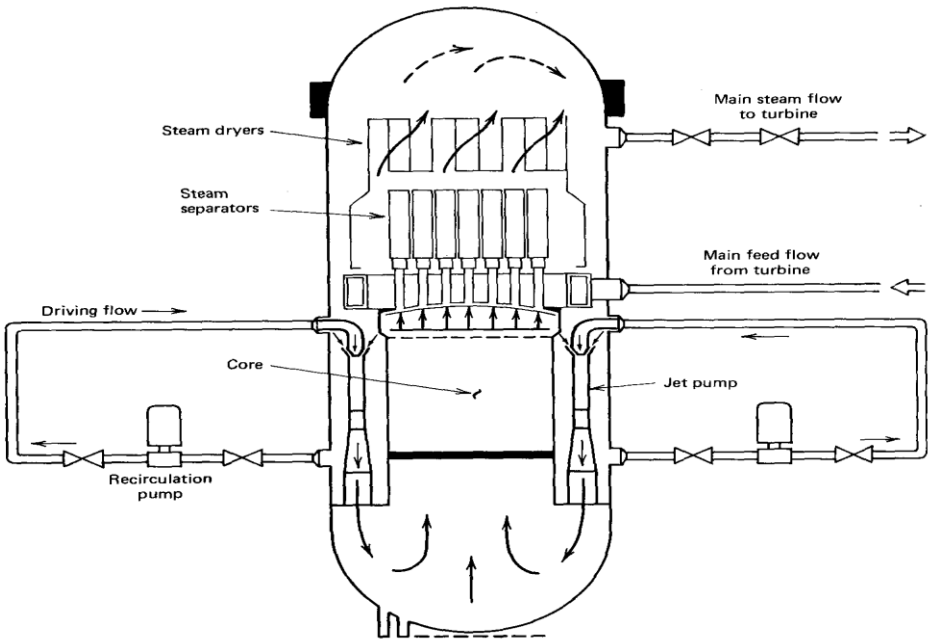


Figure2.19 Steam and recirculation water flow paths of BWR reactor.

Gas Cooled Reactor and Advanced Gas Cooled Reactor

There are a number of versions of the reactor in use with different coolants and types of fissile fuel. In Britain the Magnox reactor has been used, in which natural uranium in the form of rods is enclosed in magnesium-alloy cans. The fuel cans are placed in a structure or core of pure graphite made up of bricks (called the moderator). This graphite core slows down the neutrons to the correct range of velocities in order to provide the maximum number of collisions. The fission process is controlled by the insertion of control rods made of neutron-absorbing material; the number and position of these rods controls the heat output of the reactor. Heat is removed from the graphite via carbon dioxide gas pumped through vertical ducts in the core. This heat is then transf 1 throu

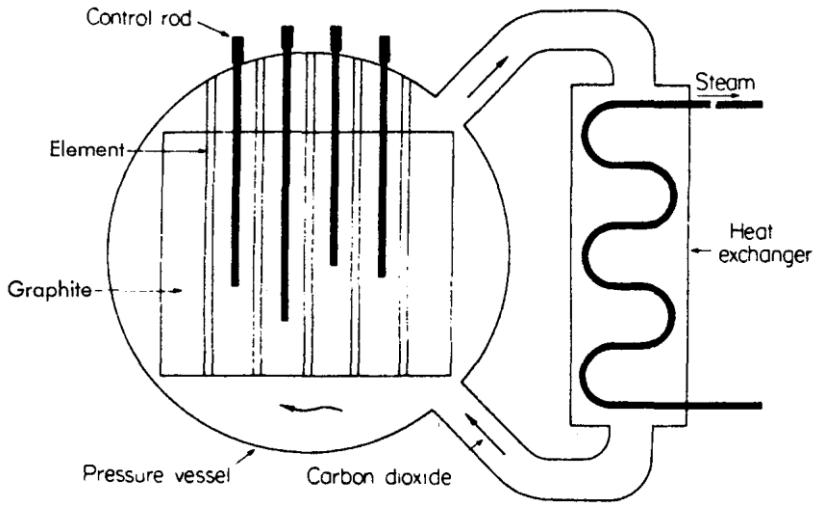


Fig.2.20 Schematic view, nuclear reactor-BRITISH Magnox type.

in a coal- or oil-fired boiler. A schematic diagram showing the basic elements of such a reactor is shown in Figure 2.20.

A reactor similar to the Magnox is the advanced gas-cooled reactor (AGR). A reinforced-concrete steel-lined pressure vessel contains the reactor and heat exchanger. Enriched uranium dioxide fuel in pellet form, encased in stainless steel cans, is used; a number of cans form a cylindrical fuel element which is placed in a vertical channel in the core. Carbon dioxide gas, at a higher pressure than in the Magnox type, removes the heat. The control rods are made of boron steel. Spent fuel elements when removed from the core are stored in a special chamber for about a week and then dismantled and lowered into a pond of water where they remain until the level of radioactivity has decreased sufficiently for them to be removed from the station.

Nuclear power plants in commercial operation

Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	US, France, Japan, Russia	264	250.5	enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	86.4	enriched UO_2	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	43	23.6	natural UO_2	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	UK	18	10.8	natural U (metal), enriched UO_2	CO_2	graphite
Light Water Graphite Reactor (RBMK)	Russia	12	12.3	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Japan, France, Russia	4	1.0	PuO_2 and UO_2	liquid sodium	none
Other	Russia	4	0.05	enriched UO_2	water	graphite
	TOTAL	**439**	**384.6**			

.

Economics of Energy Resources Dr.M.T.Lazim
Chapter Three Alternative Sources of Energy
Renewable Energy for Power Generation

Solar Energy—Thermal Conversion

There are two distinct applications: (1) space and water heating on a domestic scale; and (2) central station, large-scale heat collection, used for steam raising to generate electricity; both of these influence power systems. The former affects the load demands and in particular the problem utilities will face in having to provide a sufficient back-up supply to customers who normally would use solar power, but in certain weather conditions would require large amounts of electricity. This involves the provision of the normal amount of utility plant but with much reduced sales of energy.

As the temperature of a solar collecting surface rises it radiates heat (infrared). The energy distributions with wavelength of solar energy and infrared radiation are shown in Figure 3.1. It is possible to design a selective cover plate over the collecting surface such that it would pass nearly all the solar radiation and reflect all the radiated infrared. Selective absorbers consist of a smooth metallic sheet covered with either a thin semiconducting surface or a finely divided metallic powder. The former reflects the infrared and provides a good thermal contact between the hot absorbing layer and cooling fluid. A diagram of a simple collecting system is shown in Figure 2.13.

The energy received by the collector per square meter (net):

$$q = I\alpha\tau - (\varepsilon_F + \varepsilon_B)\sigma(T^4 - T_0^4)$$

where

ε_F and ε_B = front and back emissivities of absorber;
σ = Stefan-Boltzmann constant $= 5.67 \times 10^{-8} \mathrm{W/m^2K^4}$;
τ = transmittance of cover plate (e.g. 0.93);
T_0 = temperature of cover plate (K);
I = incident radiation normal to surface;
$T(K)$ and α = temperature and absorptivity of absorbing panel.

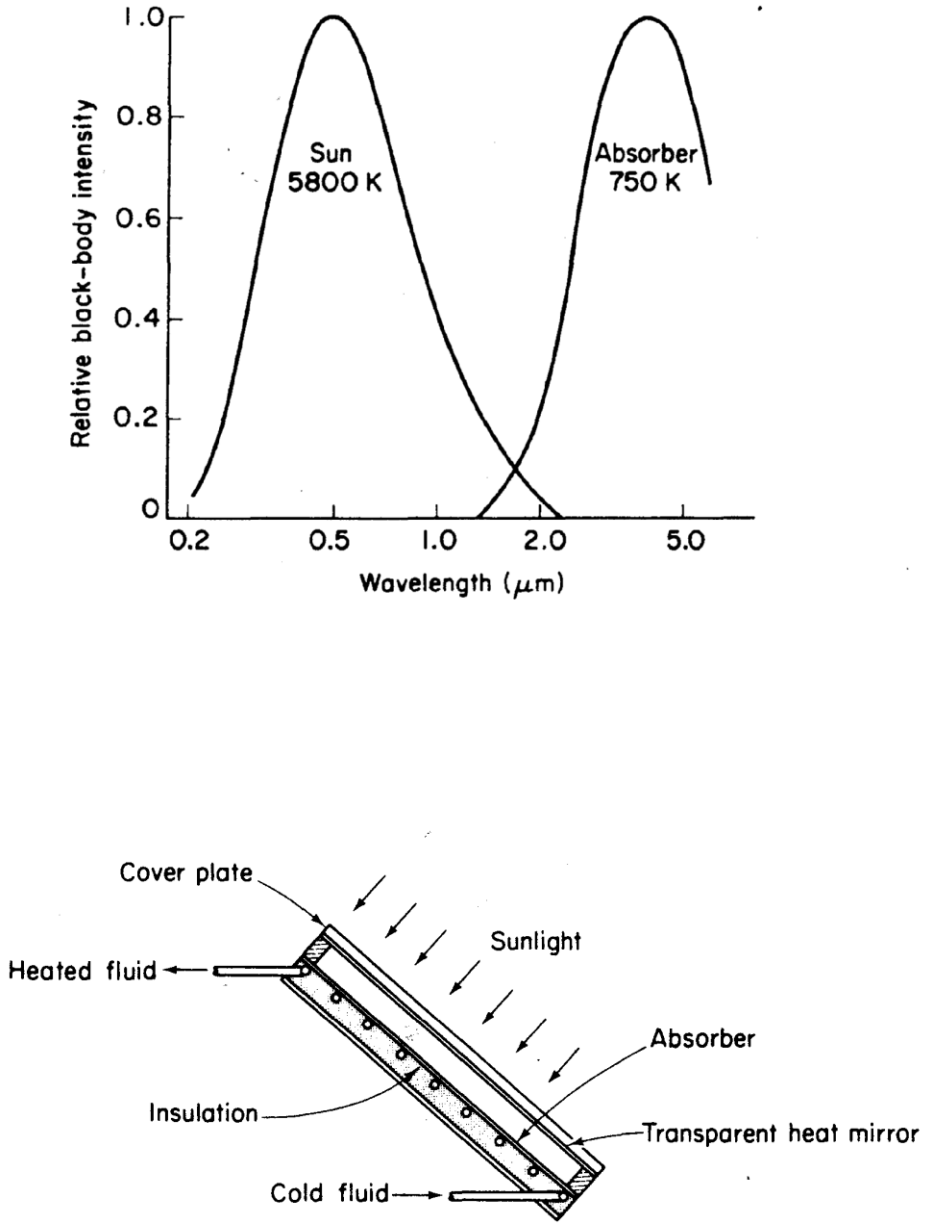


Figure 3.1 Simple solar energy panel for water heating.

In large-scale (central station) installations the sun's rays may be concentrated by lenses or mirrors. Both require accurately curved surfaces and steering mechanisms to follow the motion of the sun. Concentrators may be designed to follow the sun's

seasonal movement, or additionally to track the sun through the day. The former is less expensive and concentration factors of 30 have been obtained. However, in the French solar furnace in the Pyrenees, two-axis mirrors are used and a concentration factor of 16000 is achieved. A diagram of the central receiver system for major generation of electricity is shown in Figure 3.2. The reflectors concentrate the rays on to a single receiver (boiler), hence raising steam. A collector area of 1 km2 for each 100 MW (e) of output has been suggested with capital costs of $30/m2 (mirrors, etc.) and thermal storage costs of $15 per kWh of electricity. A less attractive alternative to this scheme (because of the lower temperatures) is the use of many individual absorbers tracking the sun in one direction only, the thermal energy being transferred by a fluid (water or liquid sodium) to a central boiler.
In all solar thermal schemes, storage is essential because of the fluctuating nature of the sun's energy, although it has been proposed that the schemes be used as pure fuel savers. This feature is common to all of the sources discussed, with the exception of geothermal, and constitutes a very serious drawback sources, as well as fluctuating loads, would complicate still further the process of electricity supply.

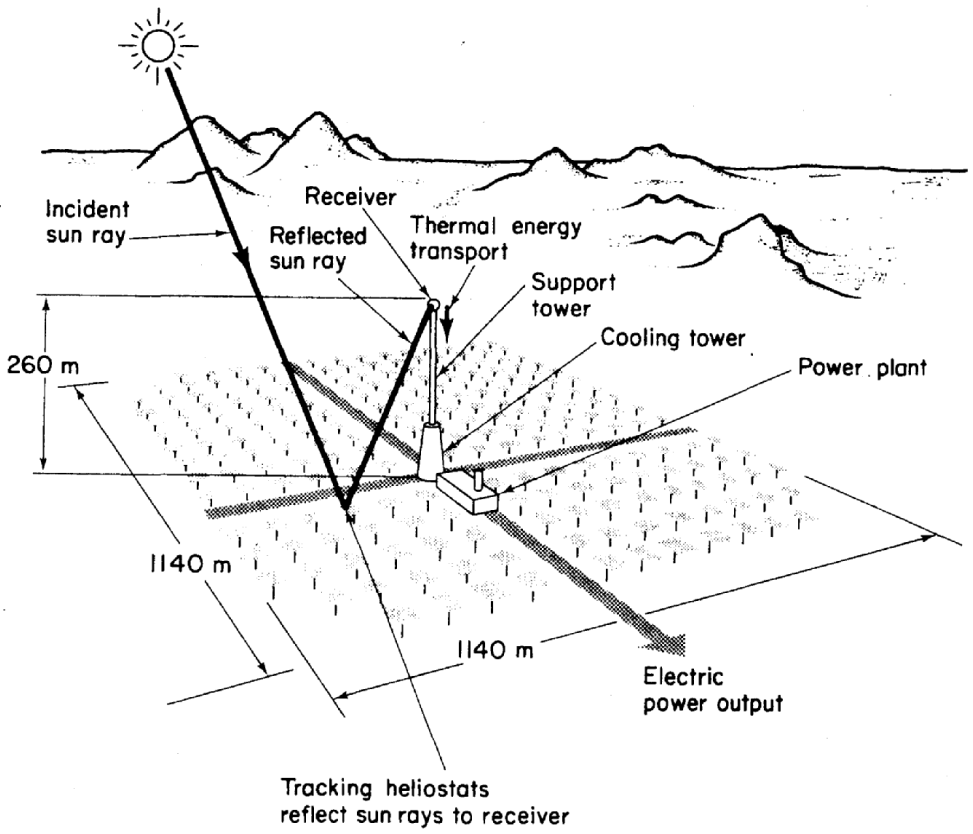


Figure 3.2 Central receiver scheme for electric power generated by solar energy

Solar Energy—Direct Conversion to Electricity

Photovoltaic conversion occurs in a thin layer of suitable material, e.g. silicon, when hole- electron pairs are created by incident solar photons and the separation of these holes and electrons at a discontinuity in electrochemical potential creates a potential difference. Whereas theoretical efficiencies are about 25 percent, practical values are lower. Single-crystal silicon and gallium-arsenide cells have been constructed with efficiencies of 10 and 16 per cent, respectively. The cost of fabricating and interconnecting cells is high (used mainly, to date, in spacecraft). Polycrystalline silicon films having large-area grains (i.e. long continuous crystals) with efficiencies of over 16 per cent have been made by techniques amenable to mass production. Although these devices do not pollute, they will, in the large-power context, occupy large areas. It has been estimated that to produce 1012 kWh per year (about 65 per cent of the 1970 U.S. generation value) the necessary cells would occupy about 0.1 per cent of the U.S. land area (highways occupied 1.5 per cent in 1975), assuming an efficiency of 10 per cent and a daily isolation of 4 kWh/m2. Automated cell production can now produce cells at around US $5 per watt.

Other forms of conversion of lesser large-scale importance come under the heading of thermoelectricity. The See beck effect gives a potential difference between pV/K. Solar the hot and cold ends of joins of different metals, a typical value being energy can heat a cathode of a diode-type tube from which electrons will be liberated by thermionic emission. These electrons drift to the anode and return through the external circuit. It is doubtful whether these devices will make any impact on the energy situation .

Problem

A glass—covered, thermally-insulated, flat-plate solar collector is used to indirectly heat the water in a storage tank of 50 gallons capacity. Water is pumped through the collector at 20×10^{-6} m3/s on a warm, sunny day when the mean temperature difference between the inflow and outflow is 17°C. If the effective area of the collector is 3 m^2 and it is 50% efficient what is the temperature rise of the water in the storage tank after 4 hours? What is the power rating per unit area of the solar collector?

Sketch a diagram of such a system and calculate the power rating required of the pump motor if the water is raised through a mean height of 2 m.

Sketch and briefly describe the operation of the solar collector.

Tides

An effective method of utilizing the tides is to allow the incoming tide to flow into a basin, thus operating the turbine, and then at low tide to release the stored water, again operating a set of turbines. This gives continuous, if varying, head operation. If the tidal range from high to low water is h (m) and the area of water enclosed in the basin is A (m^3), then the energy in the full basin

$$= \rho g A \int_0^h x \, dx$$
$$= \tfrac{1}{2}\rho g h^2 A$$

The total energy for both flows is therefore twice this value, and the average power is $\rho g A h^2/T$, where T is the period of tidal cycle, normally 12 h 44 min. The number of sites with good potential is small. Typical examples of those which have been studied are listed below, along with values of h, A, and mean power, respectively.

Passamaquoddy Bay (N. America)	5.5 (m), 262 (km2), 1800 (MW)
Minas-Cohequid (N. America)	10.7, 777, 19900
San Jose (S. America)	5.9, 750, 5870
Severn (U.K.)	9.8, 70, 8000

Wind generators

Wind power from horizontally mounted generators on 30—50 m high towers is now becoming economically viable. Sizes between 300 and 500 kW driven by two or, more effectively, three-bladed wind turbines are an optimum but larger turbines of 2—3 MW have been built for development purposes. However, the larger towers and blades for higher outputs must be traded against the extra capital costs.
The theoretical power in the wind is given by:

Principles of Wind Power

The total power of a wind stream is equal to the rate of the kinetic energy of that stream ,or

$$P_{tot} = \frac{1}{2} m_v U^2$$

Where

P_{tot} = Total power ,W.
m_v = mass flow rate kg/s
U = mean air velocity m/s

The mass flow rate is given by the continuity equation

$$m_v = \rho A U$$

ρ= density of air (1.201 kg/m^3 at NTP) = P/RT
P= pressure in Pascal
R = gas constant
T= temperature in Kelvin.
A = cross sectional area of air stream= swept area of the blade.

Hence

$$\mathbf{P_{tot} = \frac{1}{2} \rho A U^3}$$

This total power cannot all be converted to mechanical power , however maximum power obtained can be proven to be

$$P_{max} = \frac{8}{27} \rho A U^3$$

Hence the maximum theoretical efficiency η_{max} is

$$\eta_{max} = P_{max}/ P_{tot} = \frac{16}{27} = 0.5926 \cong 60\%$$

Hence wind turbine is capable of converting only 60% of the total power of the wind to a useful power.

The range of operation of a wind turbine depends upon the wind speed and is depicted in Figure 3.3.
At low wind speeds, there is insufficient energy to operate the turbine coupled to the generator and no power is produced. At the 'cut-in' U, speed, between 3 and 5 m/s on the diagram, power starts to be generated until rated power Fr is produced at rated wind speed Ur. After this point, the turbine is controlled, usually by altering the blade angle or 'pitch', to give rated output up to a maximum wind speed Uf, after which the blades are 'furled' and the unit is shut down to avoid excessive wind loading.
Typically, wind turbines have rotors of 20 m diameter, rotate at 100—150 rpm, and are geared up to about 750 r.p.m. to drive an eight-pole induction generator excited by a 415 V three-phase (3 ph.), 50Hz rural distribution system. If they are sited in 'windy' areas, normally found on exposed ridges, and can convert nearly half the theoretical power to electrical energy.

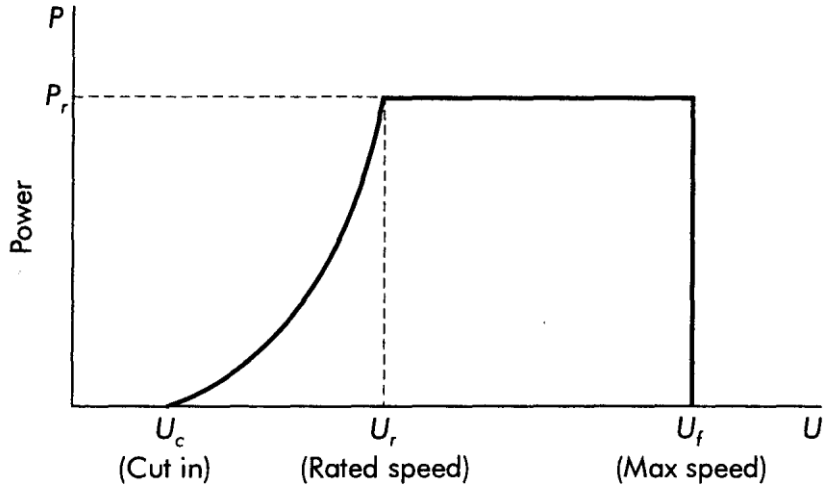


Figure 3.3 Range of operation of wind turbine.

Example 1:

Calculate the number of wind generators required to produce the equivalent of a 600MW CCGT operating at 80 per cent load factor. Assume average wind speed is (2.78 m/s), blade diameter is 20 m, and conversion efficiency is 45 per cent .

Solution:

The total power $P_{tot} = P_{wind}$

$$P_{\text{wind}} = \tfrac{1}{2} \cdot 1.201 \cdot \pi\left(\frac{20}{2}\right)^2 \cdot 2.78^3 \times 10^{-3} = 4053\,\text{kW}$$

$$P_{\text{generate}} = 4053 \times 0.45 = 1823\,\text{kW}$$

$$\therefore \text{ No. of wind generators for 600 MW} = \frac{600}{1.83} = 330 \text{ generators}$$

Example 2 :

A 10 m/s wind at 1 standard atm pressure and 15 C° temperature . This wind is acting on a wind turbine-generator with 120 m blade and 40% efficiency. Calculate:

(a) The total power density (W/ m^2) in the wind stream

(b) The maximum obtainable power density (W/m^2) .

(c) A reasonable power density (W/m^2).

(d) The total power (in kW) produced.

(e) What are the number of wind generators required to produce the equivalent of 120 MW combined cycle gas turbine unit power.

Solution :

(a) For air ,the gas constant R= 287 J/kg.K

1atm = 1.01325 x 10^5 Pa

Air density $\rho = P/RT$

T = 15 + 273 K = 298 K

$$P = \frac{1.01325 \times 10^5}{287 \times 298} = 1.226 \text{ kg/m}^3$$

$$P_{tot} = \frac{1}{2}\rho A\ U^3$$

The total power $P_{tot}/A = \frac{1}{2}\rho U^3 = \frac{1}{2} \times 1.226 \times (10)^3 = 613 \text{ W/m}^3$

(b) Maximum available power density $P_{max}/A = \frac{8}{27}\rho U^3 = \frac{8}{27} \times 1.226 \times (10)^3$

$= 363 \text{W/m}^3$

(c) since $\eta = 40\%$

Reasonable power density $= \eta\ (P_{tot}/A) = 0.4 \times 613 = 245 \text{ W/m}^3$

(d) Total power in kW :

$$\mathbf{P_{tot}} = \frac{1}{2}\ \rho A U^3 = \frac{1}{2} \times 1.226\ (\pi D^2/4) \times 10^3$$

$= \frac{1}{2}$ x 1.226 (π x $120^2/4$) x 10^3

= 2770 W

(e) The required no. of wind- generators = 120 MW / 2.77 MW

= 44

From these calculations, it is apparent that many wind generators spread over a wide area would be required. Although the ground beneath them could be used for grazing, the proliferations and the acoustic noise can be detrimental to the environment. However, the saving in CO2 emissions would be of the order of 12000 t/day provided that the wind was always blowing.

Biofuels

Biofuels are derived from decaying vegetable matter produced by agriculture or forestry operations or from waste materials collected from industry, commerce, and residential households. As an energy resource, biomass used as a source of heat by burning wood, dung, etc., in developing countries is very important and contributes about 14 per cent of the world's energy requirements. Biofuel can be used to produce electricity in two ways:

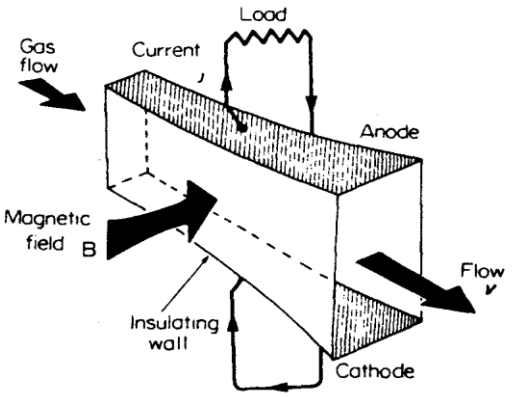
(1) by burning in a furnace to produce steam to drive turbines; or

(2) by allowing fermentation in landfill sites or in special anaerobic tanks, both of which produce a methane-rich gas which can fuel a spark ignition engine or gas turbine. It is interesting to note that if crops are cultivated for combustion, either as a primary source of heat or as a by-product of some other operation, they can be considered as CO2 neutral, in that their growing cycle absorbs as much CO2 as is produced by their combustion. In industrialized countries, biofuels have the potential to produce up to 5 per cent of electricity requirements if all possible forms are exploited, including household and industrial waste, sewerage sludge (for digestion), agricultural waste (chicken litter, straw, sugar cane, etc).

Magneto hydrodynamic (MHD) generation

The fuel used is coal, oil, or nuclear, the result is the production of steam which then drives the turbine. Attempts are being made to generate electricity without the prime mover or rotating generator. In the magneto hydrodynamic method, gases at 2500°C are passed through a chamber in which a strong magnetic field has been created (Figure 3.4). If the gas is hot enough it is electrically slightly conducting (it is seeded with potassium to improve the conductivity) and constitutes a conductor moving in the magnetic field. An electromotive force (e.m.f.) is thus induced which can be collected at suitable electrodes. Nowadays, MHD is not seen as an economically viable option compared with CCGT alternatives.

Fig.3.4



Chapter 4 Economic Considerations

Many factors influence the cost of electricity. As is true of other commercial products, the cost of electricity is made up of:

1. Fixed costs
2. Variable Costs

The fixed cost generally remains constant regardless of the number of hours the facility is used. The variable cost is the cost related to the production level of the facility.

In the electric power business, the fixed cost is entirely dependent on the capital investment. The components of fixed cost are rate of return, depreciation rate, administrative and general expenses, insurance expenses, and taxes. These .components are defined as follows :

(i) **Rate of return (Interest Rate).** It is the minimum acceptable percentage return on the invested capital. Sometimes it is referred to as the cost of capital, the discounted .rate, or the interest rate.

(ii)**Depreciation rate**. There must be periodic depreciation charges to the income in order to recover the cost of equipment before its usefulness is exhausted. The annual depreciation charge in terms of the percentage of capital investment is

$$D_r = \frac{R}{(1+R)^{n-1}}$$

where

Dr = depreciation rate expressed as a fraction

R = rate of interest expressed as a fraction

n = plant economic life in years

(ii)**Administrative and general expenses**. These expenses cover administrative and general salaries, miscellaneous materials and supplies, and any other expenses that are not accounted for in the other components. The administrative and general expenses .will be expressed as a percentage of invested capital.

(iv**) Insurance expenses.** These cover insurance against accidents to equipment and . personnel as a result of fire, windstorm, hail, flood, earthquake, and the like. Insurance expenses are expressed as a percentage of invested capita

(v).**Taxes.** This expense deals with property-related and income taxes, payroll taxes, and other miscellaneous taxes. This tax component is expressed as a percentage of the invested capital.

The sum of these five components is frequently called the **total fixed charge rate**. Evidently, the total fixed charge rate is also expressed as a percentage of the invested capital. Table 1 shows the typical values of total fixed-charge rate and its components.

In an electric utility operation the variable cost mainly consists of two components: (1) fuel cost and (2) operation and maintenance cost.

1.Fuel Cost

The largest item of expense in the operation of thermal power plant is the original raw energy. This energy may be in the form of coal, nuclear, oil, natural gas, wood scrap, or other by-products. The fuel cost varies with the plant's efficiency, unit fuel cost, and the amount of electric energy produced. The fuel cost pattern is generally predicted over the economic life of the project after taking into account escalation in the cost of materials, labor, and transportation. From this information a levelized fuel price can be computed. The levelized concept is discussed later in this chapter.

2. Operation and Maintenance Cost

Operating and maintenance (O & M) expenses include operating labor, materials, and tools for plant maintenance on both a routine and emergency basis. These expenses are neither a function of plant capital cost nor plant generating capacity. They vary from year to year and generally become higher as the plant becomes older. These expenses also vary according to the size of plant, type of fuel used, loading schedule, and operating characteristics (peaking or base load). Accordingly, the operation and maintenance expenses are generally estimated in dollars per year taking into consideration the previously mentioned factors, including estimated escalations. From such an estimate, a levelized operation and maintenance expense can be computed. In general, O & M expenses are approximately equal to one-four of the fuel expenses.

Table -1

Typical Values of Total Fixed Charge and Its Components

Rate of return	**8–12%**
Depreciation	**0.25–0.40%**
Administrative and general expenses	**0.5–2.9%**
Insurance	**0.05–0.25%**
All taxes	**2.0–5.0%**
Fixed-charge rate	**10.80–20.55%**

EXAMPLE 4-1. A coal-fired power plant of net output 582,600 kW was designed with the following economic factors :

Plant life	35 years
Fixed charge rate	11.638%
Fuel cost in the first year of commercial operation	$ 1.25 / MBtu
Fuel cost escalation rate over the plant life	7.0%

Value of installed capacity in the first year of commercial operation	$ 866/km
The rate of return	7.358 %

This plant will have the following net plant heat rate :

Loading Number	Plant Net Output (kW)	Plant Net Heat Rate (Btu / kWh)
1	643,500	9,650
2	582,600	9,650
3	399,900	9,800
4	217,100	10,125
5	0	—

Operation hours are shown in the following table:

Plant Age (Years)	Loading Schedule (hr / year)				
	1	2	3	4	5 (Down Time)
1	438	517	1071	2102	4632
2–4	438	885	1927	2278	3232
5–7	438	1332	2628	2628	1734
8–11	438	4468	1314	876	1664
12–35	438	5081	876	438	1927

Calculate for the first year of operation (1) the fuel cost, (2) the operation and maintenance cost, (3) the fixed cost, and (4) the unit generation cost in terms of mills/kWh .

Solution: The following equation is used to calculate the fuel cost of each loading

(Fuel cost) = (plant net output) (hours of operation)
x (plant net heat rate) (unit fuel cost)

At loading 1

$$(FC)_1 = (643{,}500)(438)(9650)(1.25 \times 10^{-6})$$

$$= \$3.399 \times 10^6$$

At loading 2

$$(FC)_2 = (582{,}600)(517)(9650)(1.25 \times 10^{-6})$$

$$= \$3.633 \times 10^6$$

At loading 3

$$(FC)_3 = (399{,}900)(1071)(9800)(1.25 \times 10^{-6})$$

$$= \$5.246 \times 10^6$$

At loading 4

$$(FC)_4 = (217{,}100)(2102)(10{,}125)(1.25 \times 10^{-6})$$

$$= \$5.775 \times 10^6$$

The fuel cost for the first year is then

$$(FCOST) = (FC)_1 + (FC)_2 + (FC)_3 + (FC)_4$$

$$= (3.399 + 3.633 + 5.246 + 5.775) \times 10^6$$

$$= \$18.053 \times 10^6$$

This calculation is based on the assumption that the zero load input can be completely neglected. For the O & M cost it is approximated as 25% of the fuel cost. That is,

$$(OMCOST) = (\text{fuel cost})(0.25) = (18.035 \times 10^6)(0.25)$$

$$= \$4.514 \times 10^6$$

The fixed cost for the first year is

$$= (\text{unit capital cost})(\text{unit rating})(\text{fixed charge rate})$$

$$= (866)(582{,}600)(0.11638)$$

$$= \$58.717 \times 10^6$$

The unit generation cost for the first year is

$$(GCOST) = (\text{annual fuel cost} + \text{annual O \& M cost} + \text{fixed cost})$$

$$/(\text{kWh generated in the year})$$

$$= (18.053 + 4.514 + 58.717) \times 10^6$$

$$/(438 \times 643{,}500 + 517 \times 582{,}600 + 1071 \times 399{,}900$$

$$+ 2102 \times 217{,}000)$$

$$= \$0.05539/\text{kWh or } 55.39 \text{ mills/kWh}$$

PRESENT WORTH

The power plant economic life is generally 30 to 45 years. The value of annual operation expenses is related to the time these expenses occur. Because of this, the concept of present worth must be utilized. The present worth is the value of a sum of money at the present time that, with compound interest, will have a specified value at a certain time in the future. Let

S = the sum of money at the nth year

i = annual interest rate

n = the year n

Then, the present worth (P) of S dollars at the nth year is

$$P = \frac{1}{(1+i)^n} S$$

The term $(1+i)^{-n}$ is frequently referred to as the single payment present worth factor (PWF). Table 3-2 gives these factors for the compound interest of 6%.

On many occasions equal amounts of annual expenses are required. Then the present worth of a uniform annual series of payments is calculated by

$$P = \frac{1-(1+i)^{-n}}{i} A$$

where A = annual payment.

The term $[1-(1+i)^{-n}]/i$ is often called the series present worth factor ($SPWF$). These factors for the compound interest of 6% are presented in Table 3-2.

KELVIN'S LAW

The design of a distributor is governed mainly by the consideration of voltage drop. A distributor cannot be loaded to its current carrying capacity because such a loading would result in an excessive voltage drop. On the other hand, the voltage drop is not such a vital factor in the design of a feeder and, therefore, a feeder can be designed on the basis of current carrying capacity and minimum cost.

The cost of a conductor is made up of two components:

(a) The interest on the capital cost of purchase and installation- of conductor (plus an allowance for depreciation).

(b) The cost of energy loss due to conductor resistance and in the case of cables, losses in metallic sheath and insulating material.

For a given length of the line, the weight and, therefore, the cost of conductor is proportional to the area of cross-section of the conductor. Hence, the annual cost due to interest and depreciation is also proportional to the cross-section. It can be written as $ P x a where P is a constant and a is the area of cross--section.

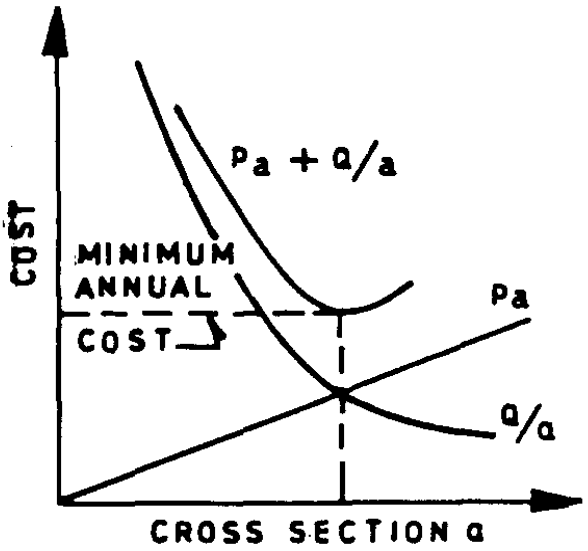
The conductor resistance is inversely proportional to the area of cross-section. For a given loading throughout the year, the energy loss is proportional to the resistance and, therefore, inversely proportional to the area of cross-section. Hence the energy loss can be written as $ (Q/a) where Q is a constant.

$$\text{Total cost } C = Pa + \frac{Q}{a}$$

For the total cost to be minimum dC/da must be zero

$$\frac{dC}{da} = P - \frac{Q}{a^2} = 0$$

or $$a = \left(\frac{Q}{P}\right)^{0.5}$$



For this value of cross-section both the components of the total cost become equal, each being equal to √PQ. This is Kelvin's law. It states that the most economical cross-section is that which makes the annual value of interest and depreciation of the

conductor equal to the annual cost of the energy wasted in the conductor. This is illustrated in Fig. 1. The graph of Pa is a straight line through the origin and that of Q/a is a rectangular hyperbola. The total cost is minimum at the point where the graphs Pa and Q/a intersect each other.

Example 1.

Apply Kelvin's law to determine the economic cross-section for the conductor of a 3 phase 10 km long 33 kV overhead line. The line supplies a load of 4 MW at 0.8 p.f. for 10 hours a day, 2 MW at 0.8 p.1. for 6 hours a day and 1 MW at 0.8 p.f. for 8 hours a day. The line is used for all the 365 days in the year. The line cost can be taken as $ (85000+2000a) per km length of line where a is the area of cross-section in mm The resistance of aluminum conductor of length 1 m and area 1 mm s 0.0286 ohms. Energy cost is $. 0.80 per kWh.
Solution

Let the area of cross-section be a mm^2

Resistance of 1 km length of line $= \frac{0.0286}{a} \times 1000 = \frac{28.6}{a}$ ohms per phase

For 4 MW load, the current is

$$I_1 = \frac{4 \times 10^6}{\sqrt{(3)} \times 33 \times 10^3 \times 0.8} = 87.48\,A$$

Energy loss in one day due to current I_1 in 1 km length of line

$$= 3\,(87.48)^2 \left(\frac{28.6}{a}\right) \left(\frac{10}{1000}\right) = \frac{6566.1}{a} \text{ kWh}$$

For 2 MW load, the current is

$$I_2 = \frac{2 \times 10^6}{\sqrt{(3)} \times 33 \times 10^3 \times 0.8} = 43.74\,A$$

Energy loss in one day due to current I_2 in 1 km length of line

$$= 3\,(43.74)^2 \left(\frac{28.6}{a}\right) \left(\frac{6}{1000}\right) = \frac{984.9}{a} \text{ kWh}$$

For 1 MW load, the current is

$$I_3 = \frac{2 \times 10^6}{\sqrt{(3)} \times 33 \times 0.8 \times 10^3} = 21.87\,A$$

Energy loss due to 1 MW load in one day in 1 km length of line

$$= 3\,(21.87)^2 \left(\frac{28.6}{a}\right) \left(\frac{8}{1000}\right) = \frac{328.2}{a}\ \text{kWh}$$

Total energy loss in one day $= \frac{1}{a}(6566.1 + 984.9 + 328.2) = \frac{7879.2}{a}\ \text{kWh}$

Yearly cost of energy losses $= \frac{7879.2}{a} \times 365 \times 0.80 = \text{Rs}\ \frac{2300726.4}{a}$

Total cost per km of line $= 85000 + 2000a + \frac{2300726.4}{a}$

For minimum total cost, the differential of total cost with respect to a should be zero.

Thus $\quad a^2 = \frac{2300726.4}{2000} = 1150.36$

or $\quad a = 33.91$ sq. mm

The standard size nearest to this area (as per IS 398-1976) is 6/1/2 59 ACSR conductor having an aluminium area of 31 61 mm The conductor size 6/1/2 59 means 6 strands of
aluminium and 1 strand of steel each strand having a diameter of 2 59 mm The current carrying capacity of this conductor for a temperature rise of 40 is 160 A which is more than the maximum current to be carried by the feeder.

Integrated (Interconnected)Systems

INTRODUCTION

This section discusses some of the reasons why electric utility systems interconnect with neighbouring systems. Except where geographical or political barriers prevent it, the interconnection of electric systems is almost universal throughout the world. The reasons are quite simple, and always make sense no matter what system we are dealing with.

Basically, electric power systems interconnect because the interconnected system is more reliable, it is a better system to operate, and it may be operated at less cost than if left as separate parts. It is well known that interconnected systems have better regulating characteristics since a load change in any of the systems is taken care of by all units in the interconnection, not just the units in the control area where the load change occurred. This fact also makes interconnections more reliable since the loss of a generating unit in one of them can be made up from spinning reserve among units throughout the interconnection. Thus, if a unit is lost in one control area, governing action from units in all connected areas will increase generation outputs to make up the deficit until standby units can be brought on-line. If a power system were to run isolated and lose a large unit, the chance of the other units in that isolated system being able to make up the deficit are greatly reduced. Extra units would have to be run as spinning reserve, and this would mean less economic operation. Furthermore, a generation system will generally require a smaller installed generation capacity reserve if it is planned as part of an interconnected system.

One of the most important reasons for interconnecting with neighbouring systems centres on the better economics of operation that can be attained when interconnected. This opportunity to improve the operating economics arises any time two power systems are operating with different incremental costs. As Example 1 will show, if there is a sufficient difference in the incremental cost between the systems, it will pay both systems to exchange power at an equitable price. To see how this can happen, one need merely reason as follows. Given the following situation:

Utility A is generating at a lower incremental cost than utility B.

• If utility B were to buy the next megawatt of power for its load from utility A at a price less than if it generated that megawatt from its own generation, it would save money in supplying that increment of load.

• Utility A would benefit economically from selling power to utility B as long as utility B is willing to pay a price that is greater than utility A’s cost of generating that block of power.

The key to achieving a mutually beneficial transaction is in establishing a “fair” price for the economy interchange sale.

There are other, longer-term interchange transactions that are economically advantageous to interconnected utilities. One system may have a surplus of power and energy and may wish to sell it to an interconnected company on a long-term, firm supply basis. It may, in other circumstances, wish to arrange to sell this excess only on a “when, and if available” basis. The purchaser would probably agree to pay more for a firm supply (the first case) than for the interruptible supply of the second case.

In all these transactions the question of a "fair and equitable price" enters into the arrangement. In this text, the economy interchange examples that follow are all based on an equal division of the operating costs that are saved by the utilities involved in the interchange. This is not always the case since "fair and equitable" is a very subjective concept; what is fair and equitable to one party may appear as grossly unfair and inequitable to the other. The 50-50 split of savings in the examples in this chapter should not be taken as advocacy of this particular price schedule. It is used since it is quite common in interchange practices in the world economy and in "normal circumstances" appears to be non-discriminatory. Pricing arrangements for long-term interchange vary widely and may include "take-or-pay" contracts, split savings, or fixed price schedules.

EXAMPLE 1

Before we look at the pricing of interchange power, we will present an example showing the benefit of interchange power.

Two utility operating areas are shown in Figure 1. Data giving the heat rates and fuel costs for each unit in both areas are given here.

Unit Data: $F_i(P_i) = f_i(a_i + b_iP_i + c_iP_i^2)$

$$P_i^{\min} \le P_i \le P_i^{\max}$$

Unit number	Fuel cost f_i (₹/MBtu)	Cost coefficients a_i	b_i	c_i	Unit limits $P_i^{\min}$ (MW)	$P_i^{\max}$ (MW)
1	2.0	561.	7.92	0.001562	150.	600.
2	2.0	310.	7.85	0.00194	100.	400.
3	2.0	78.	7.97	0.00482	50.	200.
4	1.9	500.	7.06	0.00139	140.	590.
5	1.9	295.	7.46	0.00184	110.	440.
6	1.9	295.	7.46	0.00184	110.	440.

Area 1: Load = 700 MW

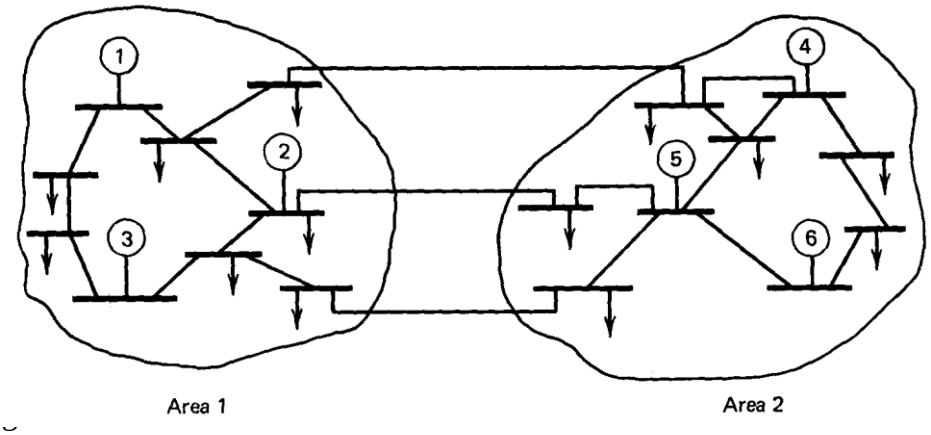
Max total gen = 1200 MW

Min total gen = 300 MW

Area 2: Load = 1100 MW

Max total gen = 1470 MW

Min total gen = 360 MW



First, we will assume that each area operates independently, that is, each will supply its own load from its own generation. This will necessitate performing a separate economic dispatch calculation for each area. The results of an independent economic dispatch are given here.

Area 1:

$$\left.\begin{aligned} P_1 &= 322.7 \text{ MW} \\ P_2 &= 277.9 \text{ MW} \\ P_3 &= 99.4 \text{ MW} \end{aligned}\right\} \quad \text{Total gen} = 700 \text{ MW}$$

$$\lambda = 17.856 \text{ ₹/MWh}$$

$$\text{Operating cost area 1} = 13{,}677.21 \text{ ₹/h}$$

Area 2:

$$\left.\begin{aligned} P_4 &= 524.7 \text{ MW} \\ P_5 &= 287.7 \text{ MW} \\ P_6 &= 287.7 \text{ MW} \end{aligned}\right\} \quad \text{Total gen} = 1100 \text{ MW}$$

$$\lambda = 16.185 \text{ ₹/MWh}$$

$$\text{Operating cost area 2} = 18{,}569.23 \text{ ₹/h}$$

$$\begin{aligned} \text{Total operating cost for both areas} &= 13{,}677.21 + 18{,}569.23 \\ &= 32{,}246.44 \text{ ₹/h} \end{aligned}$$

Now suppose the two areas are interconnected by several transmission circuits such that the two areas may be thought of and operated as one system. If we now dispatch them as one system considering the loads in each area to be the same as just shown, we get a different dispatch for the units.

$P_1 = 184.0$ MW
$P_2 = 166.2$ MW
$P_3 = 54.4$ MW
Total gen in area 1 = 404.6 MW

$P_4 = 590.0$ MW
$P_5 = 402.7$ MW
$P_6 = 402.7$ MW
Total gen in area 2 = 1,395.4 MW

Total generation for entire system = 1,800.0 MW

$\lambda = 16.990$ ₹/h

Operating cost area 1 = 8,530.93 ₹/h

Operating cost area 2 = 23,453.89 ₹/h

Total operating cost = 31,984.82 ₹/h

Interchange power = 295.4 MW from area 2 to area 1

Note that area 1 is now generating less than when it was isolated and area 2 is generating more. If we ignore losses, we can see that the change in generation in each area corresponds to the net power flow over the interconnecting circuits. This is called the interchange power. Note also that the overall cost of operating both systems is now less than the sum of the costs to operate the areas when each supplied its own load.

Example 1 has shown that interconnecting two power systems can have a marked economic advantage when power can be interchanged. If we look at the net change in operating cost for each area, we will discover that area 1 had a decrease in operating cost while area 2 had an increase. Obviously, area 1 should pay area 2 for the power transmitted over the interconnection, but how much should be paid? This question can be, and is, approached differently by each party. Assume the systems were operated with the 295.4 MW of interchange power for I h.

Area 1: Can argue that area 2 had a net operating cost increase of 4884.66$ and therefore area 1 ought to pay area 2 4884.66$. Note that if this were agreed to, area 1 would reduce its net operating cost by 13,677.21 — (8530.93 + 4884.66) = 261.62$ when the cost of the purchase is included.

Area 2: Can argue that area 1 had a net decrease in operating cost of 5146.28 $ and therefore area 1 ought to pay area 2 5146.28$. Note that if this were agreed to, area 2 would have a net decrease in its operating costs when the revenues from the sale are included of 18,569.23 — (23,453.89 + 5146.28) = 261.62 $..

The problem with this approach is, of course, that there is no agreement concerning a mutually acceptable “fair” price. In both cases one party to the transaction gets all the economic benefits while the other gains nothing. A common practice in such cases is to price the sale at the cost of generation plus one-half the savings in operating costs of the purchaser. This splits the savings equally between the two operating areas. This means that area 1 would pay area 2 5015.47$ and that each area would have 130.81 $ reduction in operating costs.

Such transactions are usually not carried out if the net savings are very small. In such a case the errors in measuring interchange flows might cause the transaction to be uneconomic. The transaction may also appear to be uneconomic to a potential seller if the utility is concerned with conserving its fuel resources to serve its own customers. This, however, is an institutional problem and not one of engineering economics.

Economics of Energy Resources	**Dr. Mohammed Tawfeeq**
Tutorial Problems- Sheets No. 1 &2	

1. A thermal power station has an overall efficiency of 21% and 0.75 kg of coal is burnt per kWh of generated energy. Determine the calorific value of coal used.

   [Ans: 5460 k.cals/kg]

2. A 6500 kW steam power station uses coal of calorific value of 15000 kCals/kg. If the coal consumption per kWh is 0.5 kg and the load factor of the station is 40%, calculate the overall efficiency and total coal consumption per day for the power station.

   [Ans: 11.47% , 312 tones]

3. A 500 MW steam power plant uses heavy fuel oil (HFO) with heat value of 43.77 MJ/kg. The specific gravity of the oil is 0.91 kg/L. If the plant overall efficiency is 30% ,calculate the quantity of heat input per hour in MJ and the fuel cost per annum if the plant is delivering its full rated output .Assume the price of a standard barrel (42-gal) of oil is 90 dollars or 0.5661 $/L.

   [Ans: $6x10^6$ MJ, 747.01627 million $/annum]

4. The input-output equation of an oil –fired power plant is generally expressed by

$$I = a + b\,(L) + c\,(L)^2 + d\,(L)^3 + e\,(L)^4$$

where I is in MBtu /hr and L is in kilowatts. Derive the corresponding expressions for the plant net heat rate and incremental heat rate.

5. A 400 MW combined – cycle plant has an input-output curve expressed by

$$I = 1.9184 \times 10^{-8}\,(L)^5 - 1.9528 \times 10^{-5}\,(L)^4 + 8.7467 \times 10^{-3}(L)^3 - 1.0945\,(L)^2 + 9003\,L + 650$$

where I is in MBtu /hr and L is in megawatts .Obtain the corresponding expression for the plant incremental heat rate.

6. A 800 MW coal-fired power plant has the plant net heat rate curve defined by

$$NHR = 0.5330 \times 10^{-7} (L)^4 - 0.1396 \times 10^{-3} (L)^3 + 0.1439 (L)^2 - 0.7089 \times 10^2 L + 0.2427 \times 10^5$$

where *NHR* is in Btu /kWh and *L* is in megawatts

(a) Derive the input-output and. incremental heat rate equations.

(b) Calculate the plant heat input at the loads, 600 MW and 700 MW. Compare the change of heat input with that obtained by integrating the incremental heat rate between 600 and 700 MW.

7. Consider a simple gas turbine cycle with the conditions described below:

Ambient air pressure and temperature	14 psia , 70 F
Compressor efficiency	0.85
Turbine inlet temperature	2200 F
Turbine efficiency	0.9
Compressor pressure ratio	11
Average constant pressure specific heat	0.25 Btu/lb - R
Specific heat ratio	1.4

Determine thermal efficiency of the cycle and net work per pound of air. Neglect the pressure drops in the combustor, compressor and turbine.

8.A hydro-station has to operate with a mean head of 30 meters and is supplied from a reservoir lake at the rate of 6.93 m^3 per second. Calculate the power generated in kW. Assume density of water 1000 kg/m^2, load factor of the station is 80%, mechanical efficiency of water turbine is 90%, efficiency of generator is 90%. .Neglect head loss in pipes, penstocks etc.

[Ans: 21.8 MW]

9.A hydroelectric station operates under a mean head of 30 meters. The reservoir employed has a catchments area of 4×10^8 m^2. The average rainfall in this area is 125 cm per annum. Determine the capacity of the station for which it should be designed. Assume that 30% of the rainfall is lost due to evaporation etc., 5% of the head is lost in penstock, turbine efficiency is 85%, alternator efficiency is 85% and the load factor is 50%.

[Ans: 4750 kW]

Economics of Energy Resources	Dr. Mohammed Tawfeeq
Tutorial Problems- Sheets No. 3 &4	

1. (a) Discuss the costs involved in generation of electrical power and the "mix" in plant used in an integrated supply system to meet a typical winter's day load curve.

(b) The demand and energy requirements of a small power system may be met either by building a single thermal power station or by building a hydro-electric station and supplementing this with a smaller thermal power station.
The maximum demand on the system is 250 MW and the load factor 42%. The hydro-electric plant is capable of a maximum output of 90 MW and energy output of 200 x 10^3 MWh per annum. Capital cost of hydro-electric plant £350 per kW. Energy cost 0.25 p per unit. For the thermal plant the costs are: Capital £180 per kW, Energy 1.0 p per unit. Interest and depreciation charges for both types are set at 18% per annum. Determine the average cost per unit for each method of supply.

2. State and prove Kelvin's Law. Suggest reasons why the law is not entirely valid for E.H.V. transmission (275 kV and 400 kV).
A consumer takes a load from his own substation of. 424.2 kW at power factor 0.707 lag using a 600 kVA transformer. Additional load of 125kW at the same power factor is to be added.
A second transformer and switchgear costing £9 per kVA is available. Alternatively loss free capacitors may be bought at £10 per kVA to raise the power factor of the total load so that the 600 kVA rating of the original transformer is not exceeded. Determine the annual cost of each scheme if the tariff charge is £12.00 per KVA of .maximum demand and interest and depreciation are charged at 12% per annum
Also find the time taken to save the initial cost of whichever additional equipment is bought.

3. By reference to a flow diagram, define the terms gross cycle efficiency and net efficiency as applied to a typical nuclear reactor power plant.
For gas-cooled nuclear reactors, discuss the factors which limit the values assigned to the quantities listed below and explain how these values affect not only the two efficiencies described above, but also the capital cost of the plant:
(i) Steam temperature at the turbine stop valve
(ii) Peak temperature within the fuel rods.
(iii) Fuel rod surface temperature.
(iv) Primary coolant temperature at reactor inlet
Comment briefly upon the major differences which would arise in the case of a water-cooled reactor.
4. Explain clearly why it is desirable to introduce the concept of reactivity in nuclear reactor technology and show how this quantity may be conveniently defined.
Describe the changes in reactivity which may occur in the core of a power reactor during commercial operation and explain how such changes may have a major bearing on:
(a) operating procedures including start up, shut down and adjustment of load
(b) the size and number of control rods;
(c) On-load refueling techniques.

5.A glass—covered, thermally-insulated, flat-plate solar collector is used to indirectly heat the water in a storage tank of 50 gallons capacity. Water is pumped through the collector at 20 x 10^{-6} m3/s on a warm, sunny day when the mean temperature difference between the inflow and outflow is 17°C. If the effective area of the collector is 3 m^2 and it is 50% efficient what is the temperature rise of the water in the storage tank after 4 hours? What is the power rating per unit area of the solar collector? .6
Sketch a diagram of such a system and calculate the power rating required of the pump motor if the water is raised through a mean height of 2 m.
Sketch and briefly describe the operation of the solar collector.

.

6.Write a dissertation explaining how you would economically run an integrated power supply system with mixed stations, and also how you would plan for the most economical ways of meeting future load demands. .7

7.State Kelvin's Law for most economical size of conductor.
A three phase, three wire line 3 km long has line voltage 11 kV and supplies, via a star-star connected transformer, a balanced load at 66 kV. The transformer efficiency is 94%. Capital cost of the line can be represented by £(400 + 1000 a) per km. (a = cross sectional area of conductor in cm2).
Running costs are charged at 075p per unit and interest and depreciation charges on capital are at
.per annum % 125
:The load is applied for a total of 6000 hours per annum and is divided thus
MW at 08 p.f. lag for 50 % of time 15
MW at 09 p.f. lag for 20% of time 3
MW at 09 p.f. lag for remainder of time 025
If 1 km of conductor 1 cm2 cross section has resistance 0004 and magnetizing currents in transformer can be neglected, calculate the most economical value for a .and also the maximum current density in each conductor
- (a) Describe, using a diagram, the essential features of an arrangement to indirectly heat the water of a domestic hot water system using a flat-plate collector. In some systems the flat-plate collector is housed in a thermally insulated container with a glass cover exposed to the incident radiation. Explain the action of the glass-fronted container .
b) A type of flat-plate solar collector has an effective area, exposed to sunlight, of 2) m by 1 m. Water is pumped through this collector at the rate 14 cm3/s and the mean temperature difference between the inflow and outflow is 15°C. The collector is used to indirectly heat the water in a storage cylinder of 40 gallons capacity. What is the temperature rise of the water in the storage cylinder after 6 hours if losses are ?neglected? What is the power rating of the flat-plate collector
-Prove that the nuclear power density at any point within the active core of a nuclear reactor is proportional to the neutron flux at the point .7
Explain how form factors may be defined to describe the spatial distribution of nuclear power density in a reactor core, and show how the magnitude of the form factors has an important influence upon both the capital costs and operating costs of a power reactor.

An experimental power reactor has a cylindrical core in which the neutron flux in any transverse plane decreases in a linear manner from the centre to the outside of the active core, the flux at the outside being 85 per cent of that at the centre. The reactor has 487 fuel channels and its rated heat output is 25 MW with a coolant temperature .rise from inlet to outlet of 480°C

Find the power rating of the central channel, and if the mean specific heat capacity of the coolant over the operating temperature range is 5l8 kJ/(kg K), determine the mass flow of coolant required in

(a) the central channel,

(b) an outside channel.

Comment on your solution.

-Explain why plutonium 239 is an inevitable by-product of the operation of a thermal reactor using uranium fuel. Explain how the amount of plutonium produced per megawatt-day differs as between a magnox reactor and an A.G.R. What is the reason for the difference.

Comment on the statement "The safest place to store plutonium is in the core of a fast reactor".

A large power system has an annual electricity output of 200,000 GWh of which 14 per cent is produced by thermal reactor nuclear stations with a net efficiency of 25.5 per cent using uranium fuel with an average enrichment of 1.07 per cent (1.5 C_o). Estimate the mass of plutonium produced per annum and the annual consumption of uranium fuel.

Approximately how much additional electrical energy could be produced by using the plutonium.

from the thermal reactors as fuel for fast reactors

Use the following data:

1 W of nuclear power is equivalent to a fission rate of 3.1×10^{10} per second .

1 tonne nuclear fuel contains 2.5×10^{27} atoms.

Natural uranium contains one atom of U235 for every 139 atoms of U238

Maximum allowable burn-up can be taken as 60 per cent.

.Any other assumptions should be pointed out and justified .

-Prove that the nuclear power density at any point within the active core of a nuclear .reactor is proportional to the neutron flux at the point

Explain how form factors may be defined to describe the spatial distribution of nuclear power density in a reactor core, and show how the magnitude of the form factors has an important influence upon both the capital costs and operating costs of a power reactor.

An experimental power reactor has a cylindrical core in which the neutron flux in any transverse plane decreases in a linear manner from the centre to the outside of the active core, the flux at the outside being 85 per cent of that at the centre. The reactor has 487 fuel channels and its rated heat output is 25 MW with a coolant temperature .rise from inlet to outlet of 480°C

Find the power rating of the central channel, and if the mean specific heat capacity of the coolant over the operating temperature range is 5l8 kJ/(kg K), determine the mass flow of coolant required in

(a) the central channel,

(b) an outside channel.
Comment on your solution.

-

Example4. By reference to a flow diagram, define the terms gross cycle efficiency and net efficiency as applied to a typical nuclear reactor power plant.
For gas-cooled nuclear reactors, discuss the factors which limit the values assigned to the quantities listed below and explain how these values affect not only the two efficiencies described above, but also the capital cost of the plant:
(i) Steam temperature at the turbine stop valve
(ii) Peak temperature within the fuel rods.
(iii) Fuel rod surface temperature.
(iv) Primary coolant temperature at reactor inlet
Comment briefly upon the major differences, which would arise

Energy Resources & Economics — Dr. Mohammed Tawfeeq

Characteristics of Power Generation Units

1. Characteristic of Steam Units

A typical boiler-turbine-generator unit is shown in Fig. A. This unit consists of a single boiler that generates steam to drive a single turbine generator set.

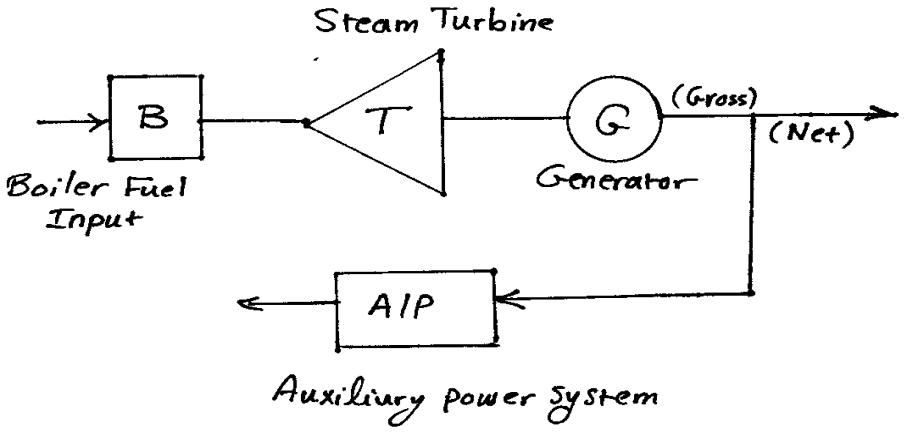


Fig. A. Boiler turbine generator unit

The electrical output of this set is connected not only to the electric power system but also to the auxiliary power system in the power plant.

A typical steam turbine unit may require (2-6)% of the gross output of the unit for the auxiliary power requirements necessary to drive boiler feed pumps, fans, condensor circulating water pumps, and so on. In defining the unit characteristics, we will talk about gross input versus net output. The gross input to the plant may be measured either in dollars per hour or million Btu / hour. The net output may be. in MW or kW.

1/uc

Unit characteristics and economic operation

The principal performance characteristic of thermal generating units is the required fuel input(H) versus power output(P). Fig.1 shows a typical curve showing the relation between fuel input and power output.

Fig.1
Input - output curve of a Steam turbine generator

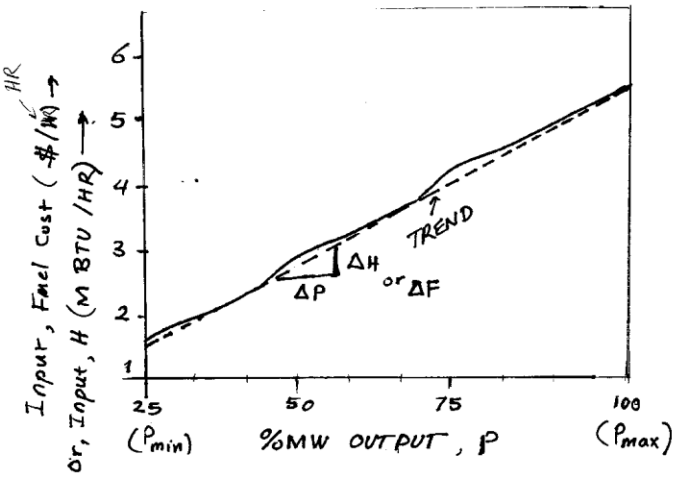


Fig.1

- A generating unit has a minimum stable output.
  - For oil and natural gas-fired fossil-steam units, the minimum stable output is typically 10 – 30%.
  - For coal-fired fossil-steam units is 20-50%.
- The incremental heat rate is defined as the instantaneous slope of Fig.1:

$$IR := \frac{\Delta \text{ fuel input}}{\Delta \text{ power Output}} = \frac{\Delta H}{\Delta P} \quad (\text{Btu/kWh})$$

Note MBtu ≡ million of Btu.

or Incremental fuel cost $\frac{\Delta F}{\Delta P}$ ($/kWh).

2/UC

If the instantaneous values of the $\frac{\Delta H}{\Delta P}$ and $\frac{\Delta F}{\Delta P}$ are ploted against the power output in (MW), the incremental heat (cost) rate curve will be as shown in Fig. 2

Fig. 2

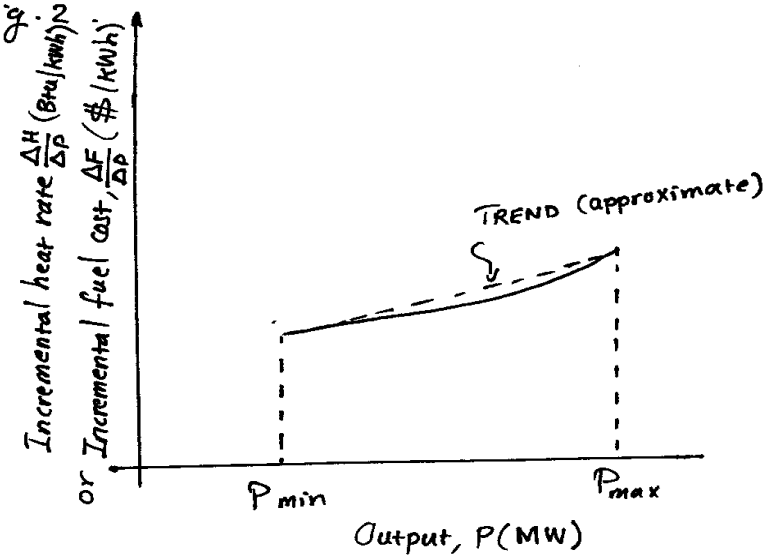
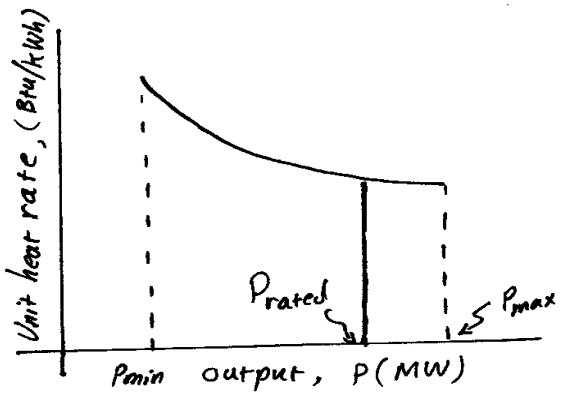


Fig. 2. Incremental heat (cost) rate characteristics.

- Generally, for simulation models, the heat rate characteristics are approximated by a series of straight lines or polynomials (trend line in Fig. 1 and 2).
- The last important characteristic of a steam unit is the average heat rate (or ~~net~~ unit (net) heat rate) characteristic shown in Fig. 3 which defined as the fuel (heat) input devided by the power output (H/P vs P).

Fig. 3
Net heat rate ch/s of a steam turbine generator unit



3/uc

• Unit Availability and Forced Outage Rates

For characterizing a generating unit or system other parameters indicating machine servicibility and dependability are required. These parameters include the service factor, availability rate, and forced outage rate. These terms are defined as follows:

$$\text{Service factor (SF)} = \frac{SH}{PH}$$

$$\text{Availability rate (AR)} = \frac{PH - (POH + MOH + FOH)}{PH}$$

$$\text{Forced outage rate (FOR)} = \frac{FOH}{FOH + SH} .$$

where:

SH = service hour (hr)
PH = Period hours (hr)
POH = Planned outage hour (hr)
MOH = Maintenance outage hours (hr)
FOH = forced outage hours

The availability and forced outage rates are extremely important parameters. They give general indication of servicibility, maintenance, and overhall cost and reliability of the generating unit.

Example: Consider a base-load unit of 800 MW in the network system in which the average energy replacement cost is 66 mills/kWh. Estimate the annual energy replacement cost if the unit has a forced outage rate of 10%. Assume that the unit has 6300 hours of service in a year.

4/uc

Solution SH = service hours = 6300

$$\text{Forced outage rate } FOR = \frac{FOH}{FOH + 6300} = 0.1$$

$FOH = 0.1\,FOH + 630$

$\therefore FOH = \frac{630}{0.9} = 700$ hours.

Then the annual energy replacement cost is

$$\begin{aligned} \text{Cost} &= (\text{unit size})(FOH)(\text{energy replacement unit cost}) \\ &= (800{,}000\ \text{kW})(700\ \text{h})(66/1000\ \#/\text{kWh}) \\ &= 36.96 \times 10^6\ \$/\text{year}. \quad (1\ \$ = 1000\ \text{mills}). \end{aligned}$$

Note: The forced outage rate has a significant impact on the unit economic performance. If the unit in the above example improves its FOR by one percent, the annual energy replacement cost will be cut down by approximately $4 million. In general, an improvement of forced outage rate in the base-load coal-fired or nuclear units will reduce the oil and gas consumption used in peaking units.

S/UC

Thermal Power Plant Performance

The performance of generating power plant can be expressed in terms of plant net heat rate as follows:

$$\text{plant net heat rate (PNHR)} = \frac{\text{Heat input (I)}}{\text{Net kW output (L)}} \quad \ldots (1)$$

$$= \frac{\text{Btu}}{\text{kWh}}$$

Now, define the incremental heat rate IR as

$$IR = \frac{dI}{dL} \quad \ldots\ldots \quad (2)$$

Hence with eq.(1), IR is expressed as:

$$PNHR = \frac{I}{L}$$

$$\therefore d(L \times PNHR) = dI$$

$$\text{or} \quad IR = \frac{d(L \times PNHR)}{dL} = PNHR + L\,\frac{d\,PNHR}{dL}$$

Example.1: A 800 MW coal-fired power plant has an incremental heat rate curve defined by

Load, MW	240	400	560	680	800
IR, Btu/kWh	7650	7800	8300	8900	10,000

or by the equation:

$$IR = 0.4818 \times 10^{-7} L^4 - 0.9089 \times 10^{-4} L^3 + 0.6842 \times 10^{-1} L^2 - 0.2106 \times 10^{2} L + 9860 .$$

6/UC

where IR is in Btu/kWh and L is in megawatts. Find the corresponding equation for the plant net heat rate.

Solution: we have $IR = \frac{dI}{dL}$

or $dI = (IR)\, dL$

Substituting for (IR) and integrating from zero to an arbitrary load L would give

$$I = 9.636 \times 10^{-9} L^5 - 2.272 \times 10^{-5} L^4 + 2.281 \times 10^{-2} L^3 - 10.53 L^2 + 9860 L + I_o .$$

where I is the heat input at the load L (10^3 Btu/hr), and I_o is the heat input at zero load. Then, the plant net heat rate (PNHR) is

$$PNHR = \frac{I}{L} = 9.636 \times 10^{-9} L^4 - 2.272 \times 10^{-5} L^3 + 2.281 \times 10^{-2} \times L^2 - 10.53 L + 9860 + I_o L^{-1} .$$

To determine the zero-load heat input I_o, it is best to make use of the fact that the plant net heat rate is approximately equal to the incremental heat rate at full load. That is

$$(IR)_{L=800} = (PNHR)_{L=800} = 10{,}000 .$$

Substitute this value into the above equation yields: $I_o = 1321 \times 10^3$ Btu/hr.

7/UC

Example 2: For the power plant described in Example 1 find the change in the plant heat input when the output increases from 600 to 700 MW.

Solution:

$$dI = (IR)\,dL$$

Substituting IR and integrating from $L = 600$ to $L = 700$ MW, it gives

$$\Delta(I) = 9.636\times10^{-9}(700^5 - 600^5) - 2.272\times10^{-5}(700^4 - 600^4)$$
$$+ 2.281\times10^{-2}(700^3 - 600^3) - 10.53\,(700^2 - 600^2)$$
$$+ 9860\,(700 - 600)$$
$$= 873{,}637\times10^3 \text{ Btu/hr}.$$

8/UC

Example : A coal-fired power plant has a turbine-generator rated at 1000 MW gross. The plant requires about 9% of this power for its internal operations. It uses 9800 tons of coal per day. This coal has a heating value of 11500 Btu/lb_m and the steam generator efficiency is 86%. Calculate the plant gross heat rate & plant net heat rate and the net steam cycle heat rate.

Solution

Rate of coal burned $= 9800 \times \frac{2000}{24} = 816,667$ lbm/h

$PGHR = \frac{816,667 \times 11500}{1000 \times 1000} = 9391.67$ Btu/kWh.

Plant net power output $= (1-0.9) \times 1000 = 910$ MW.

$PNHR = \frac{816,667 \times 11500}{910 \times 1000} = 10,320.5$ Btu/kWh.

Heat added to steam generator $= 816,667 \times 11500 \times 0.86$
$= 8.07683 \times 10^9$ Btu/h.

Net steam cycle HR $= \frac{8.07683 \times 10^9}{910 \times 1000} = 8875.64$ Btu/kWh.

The corresponding thermal efficiencies are:

plant gross efficiency $= \frac{3412}{9391.67} \times \frac{100}{100} = 36.33\%$

plant net efficiency $= \frac{3412}{10,320.5} \times \frac{100}{100} = 33.06\%$

Net cycle efficiency $= \frac{3412}{8875.64} \times \frac{100}{100} = 34.44\%$

9/UC

Economic Considerations

In all engineering works, the question of cost is of first importance. Economic problem ocurrs in the field of generation, transmission, distribution and utilization of electric power.

In the power plant design cost of energy is of the prime importance. The fuel cost is the largest item of expense in the operation of power plant. The fuel cost or price of energy varies with the amount of electric energy produced.

1. Clasification of Costs:

In general, the cost of generating electrical energy can be devided into the following elements:

(i) Fixed Cost: The components of the fixed cost are:
   (1) Rate of return (rate of interest)
   (2) Depreciation rate
   (3) Administration and general expenses
   (4) Insurance expenses
   (5) Taxes.

(ii) Variable Cost: inclues:
   (1) Fuel Cost
   (2) Operation and maintenance Cost (O&M).

O&M cost $\cong \frac{1}{4} \times$ Fuel Cost.

1/EC

Interest and Depreciation

1. Interest rate(r):

If the capital cost of a unit or plant is = P and the rate of interest per annum is r, then an amount of (rP) per annum must be provided as interest.

Normally, the interest rate may vary between 6 to 8 % per annum.

2. Depreciation rate (D_r):

After a certain time (1–40 years) the plant and machinery in an installation have to be replaced due to its aging. Therefore it is necessary to set aside certain amount every year to produce a sufficient sum at the end of the probable life for replacing the plant and machinery by new ones. This amount is known as "depreciation" and the annual rate is known as depreciation rate. The depreciation is depends on the type and make of the machines.

There are several methods for calculating the depriciation rate, one of them is called the <u>sinking fund method</u>.

Let: P = Capital cost of the plant or unit
S = Salvage value after n-years
r = Annual rate of interest

$Q = P - S$ = Cost of replacment after n-years

D_r = Depreciation rate expressed as a fraction

$$= \frac{r}{(1+r)^{n-1}}$$

$\therefore$ Annual deposit, $q = D_r \cdot Q$

$$= \frac{r Q}{(1+r)^{n-1}} .$$

Example 1: The first cost of a generating unit is 50,000 JD. It has a useful life of 20 years and a salvage value of 5000 JD. On the basis of sinking fund depreciation the interest rate compounded annually at 8%, what will be the unit value at the end of 10 years?

Solution

First cost of the plant $P = 50,000$ JD

Salvage value $S = 5,000$ JD

Total value of the sinking fund at the end of 20 years $Q = P - S = 50,000 - 5,000 = 45000$ JD.

Rate of interest $= r = 0.08$

Hence, the annual amount to be allowed for

$$q = D_r \cdot Q = \frac{r}{(1+r)^{n-1}} Q .$$

$$= \frac{0.08}{(1+0.08)^{20-1}} \times 45,000$$

$$= \frac{0.08}{4.31} \times 45,000 = 835 \text{ JD}.$$

At the end of 10 years, the sinking fund Q will be:

$$Q_{10} = \frac{q}{D_{r10}} = q \frac{(1+r)^{n-1}}{r} = 835 \times \frac{(1.08)^{10-1}}{0.08}$$

$$= 20864.6 \text{ JD}.$$

Hence, the value of the plant after the end of 10 years is $= 50,000 - 20,864.6 = 29135.38$ JD

H.W: Calculate the depreciation rate for the conditions when the economic life of equipment is 30 years and the interest rate is 15%

Fuel Cost

The original raw energy is the largest item of expense in the operation of power plant or generating unit. This energy may be in the form of coal, oil, natural gas, nuclear or other energy forms. The fuel cost may varies with:

1. Unit fuel cost
2. plant net output kW.
3. Hours of operation
4. plant net heat rate.

> Unit fuel cost is calculated on dollars per megajouls or dollars per million Btu basis

Example 1: Calculate the unit cost of a coal of heating value 27.915 MJ/kg (12000 Btu/lb) if each tonne cost 39.68 #.

Solution:

The cost of coal = $39.68 \left(\frac{\#}{\text{tonne}}\right) \times [(1000 \text{ kg/tonne})(27.915 \text{ MJ/kg})]$

$$= \frac{39.68 \times 10^{-3}}{27.915} = 0.001421 \ \#/\text{MJ}$$

$$= 1.5 \ \#/\text{million Btu}.$$

Example 2: Calculate the unit cost of oil which has a heating value of 43.733 MJ/kg. (18,800 Btu/lb) if the price of one barrel is # 28. for oil of 0.91 specific gravity.

Solution:

For standerd 42-gal barrel the price of one barrel is # 28 (# 0.17612/L).

5/EC

Heating value of the oil = 43.733 MJ/kg.
= 18,800 Btu/lb.

specific gravity = 0.91.

Cost of oil = $\frac{\$}{L}\ 0.17612 \Big/ \left[\left(43.733\ \frac{MJ}{kg}\right)\left(0.91\ \frac{kg}{L}\right)\right]$

= 0.004425 $/MJ.

= 4.67 $/million Btu.

Example 3: Compute the unit cost of natural gas:

Gas cost = 0.1201 $/m^3

= 3.40 $/ ft^3

Gas heating value = 39.#5 MJ/m^3

= 1050 Btu/1000 ft^3.

Unit Gas Cost = $\frac{\$}{m^3}(0.1201) \Big/ (39.115)\ \frac{MJ}{m^3}$

= 0.00307 $/MJ.

= 3.24 $/million Btu.

Example 4: Compute the unit cost of nuclear fuel.

Nuclear fuel cost = 75.36 $/MW day.

$$= \frac{75.36\ \frac{\$}{MW\ day}}{1.0\ \frac{J}{MW\,s} \times 3600\ \frac{s}{h} \times 24\ \frac{h}{day}}$$

= 0.00087 $/MJ.

= 0.92 $/million Btu.

5/EC

Note that :

$\$/L = (\$/42\text{-gal barrel}) \times 0.00629$.

$MJ/kg = (Btu/lb) \times 0.002326$

$MJ/m^3 = (Btu/SCF) \times 0.037255$ SCF = Standard Cubic feet.

$MJ/MWday = (\text{million Btu}/MWday) \times 1055$

$\$/MJ = (\$/\text{million Btu}) \times 0.000948$

$MJ/kW = (Btu/kWh) \times 0.001055$

$J/kWh = (Btu/kWh) \times 1055$.

$\$/m^3 = (\$/MCF) \times 0.0353$ $MCF = 1000\,ft^3$.

Fuel Cost = (plant net output)(hours of operation)
× (plant net heat rate)(unit fuel Cost) .

7/EC

Cost ③ Hours of operation ④ PNHR ·

Power Plant Economics

1. Fuel Cost : The fuel cost may varies with ① plant net output KW ② unit fuel

Fuel cost (FCOST) = (plant net output) × (hours of operation) × (plant net heat rate) × (unit fuel cost)

2. Operation & Maintenance cost of a power plant is calculated as :

OMCOST = Fuel cost × 0.25 .

3. The fixed cost for the first year of operation of a power plant is calculated as :

The Fixed cost for the first year = (Unit capital cost) × (unit rating) × (fixed charge rate)

where

fixed charge rate = Interest rate + Depreciation rate + Administrative and general expense rate + Insurance + Taxes .

4. The unit generation cost for the first year of operation

$$\text{Cost}|_{\text{generation}} = \frac{\text{Annual Fuel cost + Annual O\&M cost + fixed cost}}{\text{Annual generated kWh}} .$$

Example : A coal-fired power plant of net output 582,600 kW was designed with the following economic factors :

- Fixed cost rate	11.638%
- Unit Fuel cost in the first year of operation	1.25 $/MBtu.
- plant life	35 year
- Fuel cost escalation rate over the plant life	7.0%
- Value of the installed capacity in the first year of operation (capital cost)	866 $/kW
- The rate of interest	7.358 %

This plant will have the following net plant heat rate:

Loading Number	Plant Net Output (kW)	Plant Net Heat Rate (Btu/kWh)
1	643,500	9,650
2	582,600	9,650
3	399,900	9,800
4	217,100	10,125
5	0	—

Operation hours are shown in the following table :

plant Age (Years)	Loading Schedule (hr/year)				
	1	2	3	4	5 (Down Time)
1	438	517	1071	2102	4632
2-4	438	885	1927	2278	3232
5-35	438	5081	876	438	1927

B/EC

Calculate for the first year of operation:

(a) The fuel cost

(b) The operation and maintenance cost

(c) The fixed cost

(d) The unit generation cost in terms of mills/kW.

Solution:

(a) The following equation is used to calculate the fuel cost at each loading:

Fuel Cost = (plant net output)(hours of operation) × (plant net heat rate)(unit fuel cost)

At loading 1

$$FC_1 = (643{,}500)(438) \times (9650)(1.25 \times 10^{-6}).$$
$$= 3.399 \times 10^6 \ \#.$$

At loading 2

$$FC_2 = (582{,}600)(517)(9650)(1.25 \times 10^{-6})$$
$$= 3.633 \times 10^6 \ \#$$

At loading 3

$$FC_3 = (399{,}900)(1071)(9800)(1.25 \times 10^{-6})$$
$$= 5.246 \times 10^6 \ \#.$$

At loading 4

$$FC_4 = (217{,}100)(2102)(10{,}125)(1.25 \times 10^{-6})$$
$$= 5.775 \times 10^6 \ \#.$$

The fuel cost for the first year is then:

$$FCOST = FC_1 + FC_2 + FC_3 + FC_4$$
$$= (3.399 + 3633 + 5.246 + 5.775)10^6$$
$$= 18.053 \times 10^6 \ \#.$$

9/EC

(b) The operation and maintenance cost (O&M):

This is approximately $= \frac{1}{4} \times FCOST$.

$= 0.25 \times 18.035 \times 10^6$

$= 4.514 \times 10^6$ #.

(c) The Fixed cost for the first year is

= (Unit Capital cost)(Unit rating)(fixed charge rate).

$= 866 \times 582,600 \times 0.11638$

$= 58.717 \times 10^6$ $.

(d) The unit generation cost for the first year is

$\text{Cost}|_{\text{generation}}$ = Annual fuel cost + annual O&M cost + Fixed cost / (kWh generated in the year)

$$= \frac{(18.053 + 4.514 + 58.717)10^6}{(438 \times 643,500) + (517 \times 582,600) + (1071 \times 399,900) + (202 \times 217,00)}$$

$= 0.05539$ #/kWh

Or $= 55.39$ mills/kWh.

RPIEC

Economics of Generation

The generation of electrical energy economically is not an ordinary matter, rather it requires a long experience to decide, about the type, location and the capacity of generating plant.

For good decision, it is necessary that engineer must be familiar with the following important terms:

1. The load curves.
2. Maximum-Demand & connected loads
3. Demand factor

$$DF = \frac{\text{Maximum Demand}}{\text{Connected load}}.$$

4. Average load or demand

- Daily average load = $\frac{\text{kWh Supplied in a Day}}{24}$
- Monthly average load = $\frac{\text{kWh Supplied in a Month}}{24 \times 30}$
- Annual average load = $\frac{\text{kWh Supplied in a Year}}{24 \times 365}$

5. Load factor

$$LF = \frac{\text{Average Demand}}{\text{Maximum Demand}}.$$

6. Diversity Factor

$$DF = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand of power plant}}$$

7. Capacity (or plant) Factor

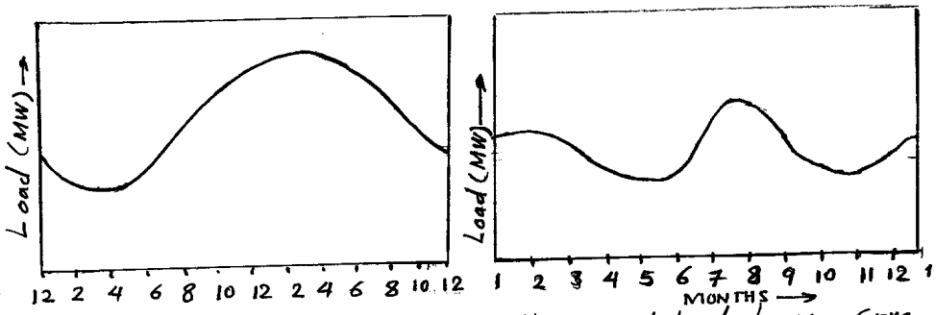
$$= \frac{\text{Average demand}}{\text{Rated Capacity of power plant}}$$

III/EC

Load Demand Representations

For economical studies, the production expenses depend on the load variations on the generating units during the year. Consequently, one should develope an accurate hourly load-model representation to facilitate cost analysis.

It is found that the 8760 hourly loads per year model (Annual load curve) is the most accurate representation. But the data required is too large. However, in less detailed simulation, a daily load-duration curve as illustrated in Fig. 1(a)&(c) is used.



(a) Typical daily load variation curve

(b) Annual load duration curve

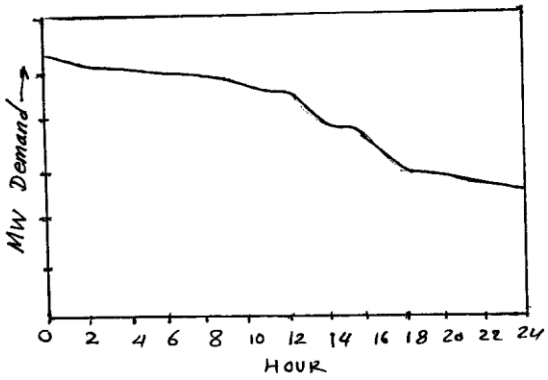


Fig. 1

(c) Daily load-duration curve

12/EC

Generation Unit Commitment

Due to daily load variations that may vary by more than 200% from peak-hour load demand through early morning load valley hours, the generating unit which is on-line for the peak hour would remain on-line for the entire day. Thus this unit (or units) would be operating at its (their) minimum power limits during the early morning valley hours.

Rather than this unit at minimum power, it may be more economical to shut this unit down overnight. If we have several units, then economical decisions must be made as to the selection of units to be shut down, the hour of the day they are to be shut down and the hour of the following day that they are to be started up again. This procedure is called unit commitment.

Economic Considerations of Unit Commitement

By developing a preliminary commitment which results in fewest number of units to be on-line to get most economical operation and hence reduction in energy demand. This can be illustrated by considering the operating cost per megawatthour versus the electrical power output characteristics of thermal units, as illustrated in Fig. 3.

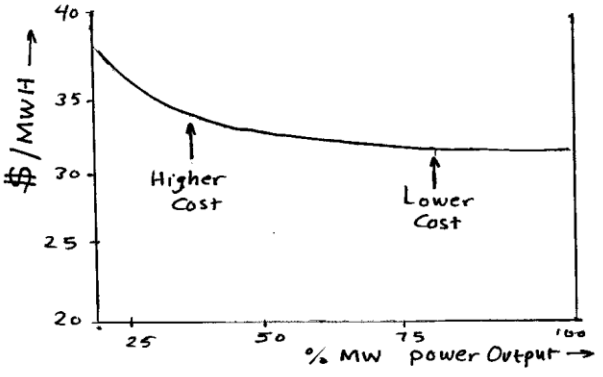


Fig. 3
Thermal Unit average operating Cost.

13/EC

The average operating cost per megawatt-hour is:

= Fuel cost + Fixed cost + Operation & maintenance costs.

- It is found that, power is more expensive to generate per kilowatt-hour when the unit operates at low power generation output than when it operates at higher output.
- However, when using unit commitment criterion, care should be taking to decrease the total unit startup costs, (the costs associated with bringing units from down to operating conditions).

  Also reserve requirement of 3-8% of load demand should be allowed for system reliability. The reserve requirements can be met with generating capacity of two types:

  (1) On-line spinning reserve

  (2) Quick-start reserve.

  - Spinning reserve is the amount of additional capacity that results from operating generating units less than full output. For example, a 1000MW unit that is operating at 700 MW output provides the system with 300 MW of spinning reserve.
  - Quick-start reserve is the amount of capacity that can be started within the required time. Gas turbines generally used for this purpose as they can be started up, synchronized and brought to full output within 10 minutes.

14/EC

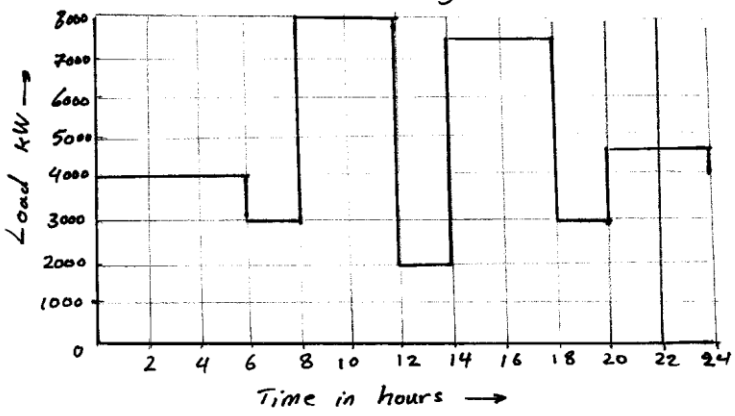
Example 1. A generating station has the following daily loads :

0 to 6 hr	4,000 kW
6 to 8 hr	3,000 kW
8 to 12 hr	8,000 kW
12 to 14 hr	2,000 kW
14 to 18 hr	7,500 kW
18 to 20 hr	3,000 kW
20 to 24 hr	4,500 kW

Sketch the load duration curve and determine the load factor and plant capacity factor assuming the capacity of the plant 11000 kW.

Solution :

1. First draw the daily load curve



Daily Load Curve

Capacity of the plant = 11,000 kW.

Maximum demand of the plant = 8,000 kW

Unit generated in 24 hours :

$$= 4,000 \times 6 + 3,000 \times 4 + 8,000 \times 4 + 2,000 \times 2 + 7,500 \times 4 + 4,500 \times 4$$

$$= 120,000 \text{ kWh}.$$

15/EC

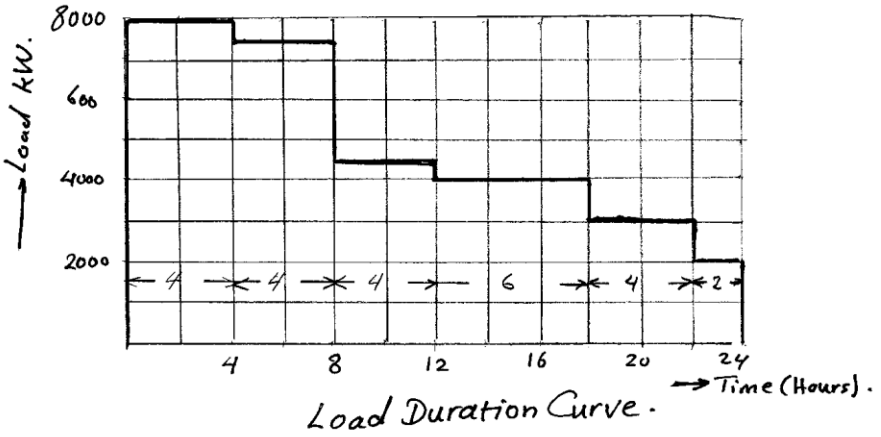
$$\text{Average load} = \frac{\text{Unit generated}}{\text{Time in hours}} = \frac{120,000}{24} = 5,000 \text{ kW}.$$

$$\text{Load factor} = \frac{\text{Average Load}}{\text{Maximum Demand}} \times 100$$

$$= \frac{5,000}{8,000} \times 100 = 62.5\% .$$

$$\text{plant capacity factor} = \frac{\text{Average load (demand)}}{\text{Rated capacity of power plant}}$$

$$= \frac{5,000}{11,000} \times 100 = 45.45\% .$$



Load Duration Curve.

16/EC

Example : The output of a generating station is 500×10^6 kWh per year and average load factor is 70%. If the annual fixed charges are 1.5 JD/kW of installed plant and annual running charges 0.15 P/kWh, what is the cost per kWh of energy at the busbar?

Solution:

Output energy per annum $= 500 \times 10^6$

$$\text{Average load (demand)} = \frac{500 \times 10^6}{24 \times 365} = 57,000 \text{ kW}.$$

$$\text{Maximum demand} = \frac{\text{Average load (demand)}}{\text{Load factor}}$$

$$= \frac{57,000}{0.7} = 81,500 \text{ kW}$$

Assuming installed capacity = maximum demand

Fixed charges $= 1.5 \times 81,500$

$= 122\,250$ JD

Running charges $= \frac{0.15}{100} \times 500 \times 10^6$

$= 750,000$ JD.

Note : (1 JD = 100 P)

Total annual charges $= 750,000 + 122\,250$

$= 872250$ JD.

Cost of energy at the busbar

$$= \frac{872250}{500 \times 10^6} = 0.0017445 \text{ JD/kWh}$$

Or $= 0.17445$ P/kWh.

17/EC